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Behaviour of Cold-Formed-Steel-Framed Walls and Floors in Standard Fire Resistance Tests

by
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A thesis submitted to the
Faculty of Graduate Studies and Research
in partial fulfillment of the requirements
for the degree of
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in Civil Engineering *

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**“BEHAVIOUR OF COLD-FORMED-STEEL-FRAMED
WALLS AND FLOORS IN STANDARD FIRE RESISTANCE TESTS”**

submitted by

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in partial fulfillment of the requirements for
the degree of

Doctor of Philosophy

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29 November 2001

Abstract

Lightweight steel framing (LSF), assembled from thin gauge cold formed steel members, is increasingly popular in commercial and residential construction in North America because of its non-combustibility, dimensional stability, ease of installation and other advantageous features. In many instances, LSF wall and floor assemblies are required to serve as fire compartment boundaries and provide adequate fire resistance, with the purpose of preventing (or delaying) the spread of fire and ensuring that building integrity is maintained while occupants evacuate and fire fighters perform suppression and rescue operations. Existing codes require the fire resistance ratings of structural assemblies to be determined on the basis of standard fire resistance tests, which are quite expensive and time consuming. As a result, in Canada, the number of LSF assemblies tested for fire resistance is extremely limited compared to the variety of designs that LSF technology can offer. The experimental part of this research thesis adds to the existing database on the fire resistance of loadbearing LSF walls protected with two layers of fire resistant gypsum board by presenting detailed results of three new tests. These tests were designed to complement earlier experiments and investigate the effect of stud spacing, cavity insulation and resilient channels on the fire resistance of loadbearing LSF walls. Test

results indicate that, contrary to generally held beliefs, cavity insulation and resilient channels reduce the fire resistance of loadbearing LSF walls while increased stud spacing does not.

In addition to standard instrumentation used in fire resistance tests, more than 50 thermocouples and ten deflection gauges were used in each test to generate temperature and deformation data suitable for analytical studies. The analytical part of this research thesis is devoted to the development and calibration of numerical modelling techniques in retrospective simulations of six wall tests and five floor tests. This task included the development of computer program TRACE for thermal simulations and computer programs STUD and JOIST for structural simulations. Theoretical structural models, presented in this thesis, form the basis of the latter two programs. Both thermal and structural simulations showed a reasonable agreement with experimental data.

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Chapter 1

Introduction and Background

Within the last decade, the use of cold-formed steel products in building construction has continued to grow and expand into new markets in North America. Cold-formed steel members can be assembled in various combinations to provide loadbearing framing systems for buildings up to 5 storeys high or used as supplemental systems together with heavy steel or concrete frames. Cold-formed lightweight steel framing is widely accepted in industrial and commercial construction. It is increasingly being used to build homes, replacing the traditional wood framing in the residential construction market. Lightweight steel framing (LSF) offers numerous advantages for savings in construction and maintenance costs:

- Steel members are of consistent quality. They are dimensionally stable: will not rot, shrink, swell, split or warp. They are noncombustible and do not require termite protection.
- Steel framing members are available in a variety of standard shapes and sizes to accommodate flexible cost-effective structural designs.

- The light weight of the framing translates into reduced foundation and seismic loads, and no heavy lifting equipment is necessary during construction.
- Steel framing members can be supplied to the exact lengths required, eliminating most of the on-site cutting and waste. Steel members are manufactured with pre-punched holes for running piping and electrical wiring, thus minimizing preparation work for utility installations.

Steel is increasingly perceived as an environmentally friendly material, because all steel products can be recycled repeatedly without degradation or loss of properties. Recycled steel is an integral ingredient in steel production. The overall recycling rate of steel products in North America is 66%, the highest rate compared to any other material.

1.1. Literature Review on the Fire Resistance of Loadbearing LSF Walls

The structural “C” section (usually with stiffening lips) is the predominant shape used for loadbearing wall studs. Other profiles, such as rectangular tubes or “Z” shapes, are also used in some systems. These sections are formed by cold rolling thin steel sheets into the desired shape. Because of their thin elements, cold-formed steel members would heat up (and lose their stiffness and strength) very quickly if directly exposed to fire. However, the gypsum board, conventionally used to form wall surfaces, provides protection for steel studs during building fires, delaying the temperature rise in the wall cavity. Figure 1.1 illustrates the typical temperature history of a steel stud within an LSF wall subjected to fire from one side. Multiple layers of gypsum board may be required to achieve the desired level of fire protection.

LSF wall assemblies are, under certain circumstances, required to provide adequate fire resistance to prevent (or delay) the spread of fire and ensure the building integrity is maintained during fires while occupants evacuate and fire fighters perform their duties. In general, the fire resistance can be determined by tests or by analytical methods. With the advent of performance-based codes, the development of reliable fire resistance analytical models for loadbearing LSF walls has become essential.

1.1.1. Current Practice of Fire Resistance Rating

The fire resistance of a loadbearing wall is its ability to withstand exposure to fire. This ability is usually expressed in terms of its fire resistance rating, which is the length of time the wall can withstand exposure to fire in a standard fire resistance (fire endurance) test (CAN/ULC-S101-M89, ASTM E119-95a, ISO 834-1 1999) without losing its loadbearing or fire separating functions. The fire resistance ratings are extensively used by building codes all over the world to express their requirements for fire resistant design.

The National Building Code of Canada (NBCC 1995) outlines the fire safety requirements for buildings in Part 3 “Fire Protection, Occupant Safety and Accessibility”. Smaller buildings of 3 storeys or less, with a building area not exceeding 600 m² (some occupancy limitations apply, see NBCC Subsection 2.1.3), can also be designed under Part 9 “Housing and Smaller Buildings”. Both Parts prescribe essentially the same fire safety requirements, however, Part 9 contains more detailed prescriptions that would

enable the design of smaller buildings to be carried out without retaining an engineer or an architect.

A wall is considered loadbearing if it forms a part of the building's structural frame resisting gravity loads. Walls subjected only to wind or earthquake loads are not considered to be loadbearing (NBCC Article 1.1.3.2) for the purposes of fire safety. The fire resistance requirements are complex functions of many factors, such as type of occupancy, building height, building area, etc. With little exception, all loadbearing walls in a storey immediately below a floor or roof assembly required to have a fire resistance rating are required to have a fire resistance rating not less than that required for the supported floor or roof assembly (NBCC Article 3.1.7.5). In addition, interior walls may be required to have a fire resistance rating if they are designated as vertical fire separations, while exterior walls will need a fire resistance rating if they do not comply with the limiting distance requirements (NBCC Article 3.1.7.2). Exterior walls are rated for exposure to fire from inside the building only, while interior walls must be rated for fire exposure from each side (NBCC Article 3.1.7.3). It should be noted that most buildings using loadbearing LSF framing systems would rarely require fire resistance ratings exceeding 1 hour for any of its components. An exception to that are mixed-use buildings where 2 hour separations are commonly required between major occupancies (NBCC Article 3.1.3.1).

Whenever an assembly is required to have a fire-resistance rating, NBCC Articles 3.1.7.1 and 9.10.3.1 specify that such a rating should be determined based on one of the following:

- Tests conducted in accordance with CAN/ULC-S101 “Standard Methods of Fire Endurance Tests of Building Construction and Materials”.
- NBCC Appendix D, “Fire Performance Ratings”, which prescribes the Component Additive Method of obtaining fire resistance ratings for generic wall, floor and roof assemblies (NBCC Subsection D-2.3). The method, however, does not apply to loadbearing LSF walls.

NBCC article 9.10.3.1 also permits ratings to be determined based on NBCC Table A-9.10.3.1 (for housing and smaller buildings), which prescribes fire resistance and sound transmission class ratings for some generic building assemblies, but does not specify fire resistance ratings for loadbearing steel stud walls.

Clearly then, neither Appendix D nor Table A-9.10.3.1 provides for loadbearing LSF walls. The experimental data on their performance under fire exposure is very limited, and there is no generally accepted analytical method to determine their fire resistance. Moreover, research studies that would lead to such a method have never been undertaken in Canada. This research project is aimed, in part, to correct this situation.

At the present time, the fire resistance rating for a loadbearing LSF wall can only be assigned based on the results of standard full-scale furnace tests. The testing procedures and acceptance criteria for loadbearing walls are described below.

1.1.2. Standard Fire Resistance Test

Full-scale fire tests, done in accordance with CAN/ULC-S101, are usually conducted on wall specimens not less than 2.75 m in length or height. Every specimen should be truly

representative of the wall assembly for which the fire rating is desired. During testing, the specimen is installed in a special wall furnace and exposed to the standard fire on one side. The wall area exposed to fire should not be less than 9.3 m^2 . The standard fire exposure is achieved by following as closely as possible the standard time-temperature relationship (CAN/ULC-S101-M89 Table 1). The actual furnace temperature is deemed to be the average temperature obtained from the readings of not less than nine thermocouples, in standard sealed porcelain tubes, symmetrically disposed and distributed 150 mm away from the exposed face of the wall sample. The standard limits the deviation of the average temperature readings from the required time-temperature regime (CAN/ULC-S101-M89 Clause 4.2.3). However, there are no limitations imposed on the deviation of the individual temperature readings from the average, i.e., the uniformity of temperature within the furnace is not specified. The standard does not contain any specific references to the pressure levels to be maintained in the furnace, although it requires the information concerning furnace pressures to be obtained from probes located at the top, mid-height and bottom levels of the wall specimen (CAN/ULC-S101-M89 Clause 5.1.4). Usually, a slight negative pressure is maintained in the fire furnace.

Throughout the fire endurance test, the wall specimen must carry a superimposed vertical load to simulate either a maximum load condition or a restricted (some fraction of the maximum) load use condition. The maximum load condition corresponds to the maximum service (or working stress) load allowed by the structural design criteria. In Canada, this load is derived in accordance with S136-94 "Cold Formed Steel Structural

Members". Note that the maximum fire test loading for a steel stud wall would be considerably less than its theoretical non-factored resistance in axial compression (between 50 and 70%, depending on the load and resistance factors used in the structural analysis). Appendix C of CAN/ULC-S101-M89 provides some guidance as to the design procedures to follow in developing the maximum loading condition for a fire test assembly. For the commonly used singly symmetric wall studs, assumed to be braced by steel lateral supports only (without sheathing), and designed for a live to dead load ratio of 4, the maximum fire test load condition would correspond to about 52% of their theoretical non-factored axial compression capacity. Note that the actual loadbearing capacity of the wall assemblies supplied for fire testing would normally be higher than the theoretical capacity due to various factors (higher than minimum specified steel yield strength, some degree of conservatism in structural design methods, etc.), and the fire test also exploits this additional safety margin. Nevertheless, most reported tests on loadbearing LSF walls indicate that structural failure of the studs occurs before significant heat or flame penetration through the wall could take place, unless the load condition is limited to an unusually low percentage.

CAN/ULC-S101-M89 requires that loadbearing wall test specimens not be restrained on their vertical edges during fire tests. It also requires deflection measurements to be taken at one location point (only), where the maximum deflection of the specimen is expected. The standard does not specify the boundary conditions at the top and bottom edges of the wall specimen, so the degree of rotational restraint at stud ends is usually unknown. There are no specific requirements pertaining to the loading system arrangements or

means of load control. The wall specimens are usually loaded through rigid spreader beams by hydraulic jacks. The total load on the wall is controlled by adjustments to the hydraulic pressure.

The loadbearing wall test is regarded as successful if the wall specimen has sustained the applied load for the desired time period of standard fire exposure while maintaining its integrity and heat separating function. The integrity failure criterion is defined by the passage of flames or gases hot enough to ignite cotton waste through the wall. The heat separating function is considered fulfilled if the temperature rise at any individual point on the unexposed surface of the wall has not exceeded 180°C and the average temperature of the unexposed wall surface has not raised more than 140°C above its initial temperature (CAN/ULC-S101-M89 Clause 7.3.4). The temperatures on the unexposed surface of the wall should be measured at not less than nine locations by thermocouples placed under special pads.

Wall assemblies, for which a one-hour or higher rating is desired, are also required to pass a hose stream test (CAN/ULC-S101-M89 Clauses 7.3.3 and 5.2.2). Immediately after the completion of the fire endurance test, the exposed face of the test specimen is subjected to the impact, erosion and cooling effects of a hose stream. Alternatively, a duplicate specimen is first subjected to fire exposure for a period equal to one-half the fire resistance period obtained from the fire endurance test (but not more than 1 hour), and then the hose stream applied. The details of the stream equipment, water pressure, nozzle distance and duration of stream application are specified in CAN/ULC-S101-M89 Subsection 5.2. Throughout the hose stream test, loadbearing wall assemblies are

required to sustain the applied load and maintain their integrity by not allowing the passage of the hose stream. Note that loadbearing steel stud gypsum board walls are highly unlikely to fail in a hose stream test.

The standard testing procedures specified by CAN/ULC-S101-M89 are essentially the same as those prescribed by ASTM E119-95a, used in the United States. However, the actual load level corresponding to the maximum (or restricted) load condition for loadbearing assemblies tested according to ASTM E119 could be different, because it would be derived from the provisions of an appropriate American structural design code. For LSF walls, this would be the “Specification for the Design of Cold-Formed Steel Structural Members” published by the American Iron and Steel Institute (AISI). It should also be noted that structural design regulations do change with time in any country. Therefore, the maximum (or restricted) load condition of fire resistance ratings for loadbearing assemblies, based on fire tests conducted many years ago, should be considered in the context of the structural design regulations in force at the time of the fire tests.

The fire resistance testing procedures adopted in other countries are, in many aspects, similar to those in North America. This similarity is especially noticeable in the standard time-temperature relationships used in various countries (Lie 1992). Therefore, the fire resistance test data for similar construction assemblies obtained in different countries is comparable to some extent. In Figure 1.2, the CAN/ULC-S101-M89 time-temperature relationship for the initial two hours of the standard fire test is compared with the

ISO 834 curve, used in Great Britain, Australia and New Zealand. The ISO curve is defined by:

$$T_f - T_0 = 345 \cdot \log_{10}(8t + 1) \quad (1.1)$$

where

t = time in minutes,

T_f = fire temperature in °C, and

T_0 = initial temperature in °C.

There have been several approximate analytical expressions proposed for the time-temperature curve used in North America (Lie 1995). The following expression is reasonably accurate and frequently used:

$$T_f - T_0 = 750 \cdot [1 - \exp(-0.49\sqrt{t})] + 22\sqrt{t} \quad (1.2)$$

Other fire endurance test parameters, such as minimum specimen size, temperature measurement arrangements, furnace pressure or acceptance criteria for the fire resistance rating, may be different somewhat from country to country. For example, most countries do not use hose stream tests, but some countries impose limitations on the temperature of steel members in the assembly or use bare (without protective tubes) thermocouples to measure furnace temperatures. Therefore, some caution should be exercised when comparing furnace test results or fire resistance ratings from different countries.

Harmathy and Sultan (1988) studied the correlation between the severity of ASTM E119 and ISO 834 fire exposures. It was found that the ISO test is slightly less severe, but differences in the fire endurance values yielded by the two tests should not be expected to exceed five minutes. It is worth to mention, however, that recent ISO 834 (1999)

requirements for positive furnace pressure are likely to make the ISO fire test exposure more severe.

1.1.3. Listed Designs

Various organizations publish directories (listings) of proprietary or generic assemblies, rated for fire resistance based on their performance during fire endurance tests. NBCC Article D-1.1.5 specifically refers to the listings of two testing organizations, Underwriters' Laboratories of Canada (ULC) and Warnock Hersey (WH), for information on fire rated assemblies (List 1993, Certification 1994). However, the only listed design for loadbearing steel stud gypsum board walls that could be found there is ULC Design No. W424. It assigns 1 hour, 1.5 hour and 2 hour ratings (depending on the number and thickness of protective gypsum board layers; some load restrictions apply) for interior wall assemblies with a single row of 92×35×0.9 mm (minimum) galvanized steel studs (lipped "C"-section) spaced 600 mm o.c. (maximum). Only mineral fibre batts and blankets processed from rock and slag may be used (optional) to fill the wall cavity. The design contains extensive information on fastener sizes and spacing. It also requires lateral bracing of the studs by horizontal 38×12 mm (minimum) galvanized steel channels passed through stiffened web perforations in steel studs and spaced 1200 mm o.c. The steel studs of ULC Design No. W424 are designated as structural components listed under the Label Service of ULC (that is, steel studs from only the two listed manufacturers are designated for use). ULC requires the constructed assemblies to duplicate the listed design in every detail in order to achieve the indicated fire resistance

rating (NBCC Subsection D-1.1.3 contains a similar requirement for assemblies that are the subject of an individual test report). Authorities having jurisdiction must be consulted before installation. Any deviations from the listed design require additional approval.

Clearly, the information provided by NBCC, ULC and WH on the design of loadbearing steel stud walls for an appropriate fire resistance rating would be insufficient in many practical situations. Therefore, most authorities having jurisdiction in Canada are likely to accept rated assemblies listed by Underwriters Laboratories Inc. (UL) operating in the United States (Fire 1994). The UL listings are based on results of fire tests conducted in accordance with ASTM E119 and contain twelve designs for loadbearing LSF wall assemblies that use gypsum board for fire protection. UL Designs U418, U460 and U472 provide fire resistance ratings for exterior walls exposed to fire on the interior face only. Designs U434, U473, U477 and U487 use gypsum board in combination with other products like Portland cement plaster on metal lath, cementitious backer units, mineral and fiber boards, etc. Designs U426 and U462 assign a 3 hour rating for loadbearing LSF walls with four layers of 12.7 mm thick fire-rated gypsum board on each side. It is the highest fire resistance rating assigned for loadbearing steel stud walls. However, the most general (and useful) UL Design for loadbearing LSF walls is listed under No. U425. It assigns up to 2 hour fire resistance ratings for a wide range of interior and exterior wall assemblies. UL Design No. U425 is partially reproduced in the Manual of the Gypsum Association (Fire 1988) as File No. WP1204, WP1206 and WP1716. UL Design No. U489 provides useful details on the fire protection of heavy steel columns within loadbearing LSF walls (it is essentially a combination of Design U425 for the wall

components and Designs X524 and X530 for steel column protection). Note that UL designs often permit either glass fibre batts or mineral wool insulation for wall cavity filling. Both straps and channels are allowed in many UL designs to provide lateral support for the studs. The designs for exterior walls permit a variety of exterior facings.

It is worthwhile to mention that the required fire resistance of loadbearing LSF walls could also be achieved using protective sheeting materials other than gypsum board. For example, UL Design No. U486 and WH Design No. PNA/WA 120-04 assign a 2 hour rating for a loadbearing steel stud wall assembly with two layers (12 and 16 mm thick) of cement bonded particle board on each side.

1.1.4. Drawbacks of the Current Practice

In general, the current practice of fire protection design is prescriptive in that the designer is told what parameter values to use rather than being able to calculate these values. With regard to the design of a loadbearing LSF wall for some prescribed fire resistance rating, the designer is limited to choosing an appropriate design from available rated assemblies. Departures from listed designs are usually difficult to justify to the satisfaction of the authorities having jurisdiction. Full-scale tests are required to establish ratings for new designs.

The standard fire test has been seriously criticized (Boring et al 1981, Purkiss 1996). The established practice of fire resistance rating for loadbearing LSF walls, based on full-scale tests, has numerous drawbacks:

- Fire resistance ratings based on standard test results do not reflect the actual time that construction assemblies would endure in a real building fire scenario.
- The declared purpose of the standard test is to provide a method for comparing the “relative” performance of various building components under similar fire exposure conditions. However, this similarity is undermined by a number of factors (Boring et al 1981). One such factor is that combustible assemblies significantly contribute to the fire intensity in the furnace, i.e. less fuel is required for combustible test specimens than for noncombustible test specimens in order to maintain the same standard time-temperature regime.
- Standard fire test procedures are mainly oriented to detect heat penetration type of failure. Very little attention is given to the structural part of fire tests for loadbearing assemblies. As a result, the methods of load application and control during fire tests vary from one testing facility to another, they are usually not reported, and their accuracy is unknown. For loadbearing wall assemblies, which fail structurally in fire tests, the importance of clearly defined structural parameters of the test cannot be overstated. Standards should be more specific with regard to loading arrangements and specimen boundary conditions.
- The test furnaces are limited in size. Therefore, only “representative” specimens could be tested.
- Full-scale fire tests are very expensive and time consuming. As a result, only a limited number of fire rated designs are available.

- Little is known about the reproducibility of fire test results. Duplicate tests are rarely undertaken due to their considerable cost, and relevant standards do not require more than one fire test in order to establish a rating. Another aspect of fire test result reproducibility is related to the differences between various fire testing facilities. Differences in loading arrangements and thermal characteristics of fire furnaces could cause significant variations in fire test results (Purkiss 1996, Sultan 1996).
- Most fire resistance test reports are confidential and usually belong to the manufacturers of the tested products (who pay for the tests). This confidentiality of test results is holding back the development of analytical methods of fire resistance assessment, since any experimental data obtained from such tests is not available for the purposes of research. Another negative aspect of test result confidentiality is that published fire resistance ratings are not open for public or independent review. This is a situation rarely tolerated in other fields that concern the safeguarding of human life or health. While it is often implied that published ratings are conservative compared to actual test results, it might not always be the case. The fire resistance ratings are usually defined to be “based” on fire test results. Such a definition allows testing agencies to exercise judgement to some (unknown) extent when assigning fire resistance ratings.
- Any serious revision or change in the standard fire test procedures (introduction of positive furnace pressure, more realistic time-temperature regimes, etc.) would be very difficult to implement, because it would necessitate the re-testing of many currently accepted fire-resistant assemblies.

The great amount of money already invested over several decades to conduct standard fire tests and the absence of an acceptable alternative are two major factors contributing to the continued use of the standard test. In spite of all the above-mentioned drawbacks, the standard fire test still provides a convenient and necessary method of fire resistance assessment, when analytical calculation methods are not available or not applicable.

1.1.5. Previous Experimental Studies

During this literature survey, publications pertaining to only four previous experimental studies of relevance were found. These studies are described below in some detail in chronological order. Most of the tests were conducted following standard fire endurance test procedures outlined in the previous section.

Son and Shoub (1973) described two fire endurance tests conducted on 4.85 m long by 2.44 m high double-wall assemblies. In both tests, the assemblies consisted of two LSF walls of similar design, separated by 12.7 mm cavity. The inner surfaces (facing the separation cavity) of the two walls in these double-wall assemblies were lined with 12.7 mm thick gypsum board, while the outer surfaces were of 15.9 mm thick gypsum board. All gypsum board sheets were of Type X, 1.22 m wide, fastened to the steel studs (and top/bottom channels) by 25 mm long bulge head screws spaced at 305 mm in the field of the boards and 203 mm along the perimeters of the boards. The distributed external vertical load of 15 kN/m (8.08 kN/stud) was applied to each wall in both tests, however, no further detail was provided with regard to the loading arrangements. Positive furnace pressure was maintained above the 0.8 m level from the bottom of the specimens.

The first assembly was constructed from 76.2×44.5×1.21 mm “C” shaped studs with 12.7 mm lips spaced 610 mm o.c. Batts of friction fit glass fibre insulation 64 mm thick were placed between the studs of each wall. The second test assembly employed 76.2×50.8×1.65 mm rectangular tube studs and 89 mm thick glass fibre insulation compressed to fit in the wall cavities. No bracing was reported for either of the two assemblies. In each test, temperature readings were recorded at 2 minute intervals from 56 thermocouples placed within the wall assembly structure and 12 thermocouples placed under asbestos pads on the unexposed outer surface. Maximum and average temperature histories at instrumented locations across the assemblies were presented in graphical format. Lateral deflections of the unexposed surface (at mid-height of the specimens) measured at the centre and two quarterpoints along the wall were reported to occur towards the fire in both tests. In the first test, structural failure of the fire-exposed wall was observed at 42 minutes, one minute after a considerable part of the fire-exposed gypsum board had fallen away. Similar structural failure of the fire-exposed wall was observed in the second test at 67 minutes (where the fall of gypsum board was reported to start at 48 minutes). Much slower heat penetration through the wall assembly occurred in the second test, and this was attributed to the thicker insulation used for that specimen. However, contrary to that attribution, the presented temperature data for the second test also indicates a much slower temperature rise in the fire exposed gypsum board. The investigators also identified the joints between the gypsum boards to be a particular source of weakness and concluded that a better practice would be the use of a two-layer

construction with staggered application of board joints to eliminate direct heat access to the steel studs when joints open.

Klippstein (1978, 1980) provided a limited description of the most extensive experimental study ever conducted on loadbearing steel stud walls. The study was sponsored by the American Iron and Steel Institute (AISI) and eventually led to UL Design No. U425. Nine wall assemblies (seven non-insulated and two insulated) were tested for fire endurance under various load intensities. Some information pertaining to another three fire tests on loadbearing insulated LSF walls, conducted earlier under the sponsorship of the US Steel Corporation (USSC), was also presented. Each of the twelve wall assemblies was 3.05 m long and typically consisted of six “C”-shaped studs (with stiffening lips), spaced 610 mm o.c., with up to three layers of fire resistant gypsum board (12.7 mm or 15.9 mm thick) on each side. In all tests, except one, the steel studs had cross-sectional dimensions of approximately 90×40×1.2 mm and yield strength ranging between 352 MPa and 407 MPa. In the last test (Panel 12), studs with dimensions of 92×41×1.9 mm and a yield strength of 237 MPa were used. Ten of the wall assemblies were 3.05 m high. The last two wall assemblies tested (Panels 11 and 12) were 0.15 m shorter in order to accommodate load cells placed under the centreline of each stud to monitor axial loads. A detailed description of these last two tests has provided measured temperature, mid-height deflection and axial load histories, which were presented graphically. The temperature measurements indicated that steel studs closer to wall ends remained at low (lower than anticipated) temperatures during the fire tests. This effect was attributed to the negative furnace pressure, which causes the cool ambient air to flow

into the furnace through the wall cavity. Both positive (towards the furnace) and negative (away from the furnace) lateral deflections of the studs were observed in both tests. The individual steel stud loads were found to vary significantly from the intended average stud load during the initial pre-loading, and this variation further increased during subsequent heating in the fire tests. The presented data indicated that, due to the high rigidity of the load spreader beam, the studs closer to the centre of the wall assembly (which, in general, heated and expanded faster than the studs at wall ends) tended to receive above average individual loads during the initial stage of the fire test. During the latter phase of the test, the total load was redistributed to the studs farther away from the centre of the wall. The load cell data also indicated that the total load applied to wall assemblies was not stable during fire tests and usually exceeded (by up to 100%) the intended load level. Klippstein (1978) advocated changes to standard fire test procedures to ensure uniformity in steel stud behaviour and reproducibility of fire test results.

Gerlich, Collier and Buchanan (1996) reported results of three fire resistance tests on LSF walls, conducted at the laboratory of the Building Research Association of New Zealand (BRANZ). This publication was based on the research report of Gerlich (1995). Two wall assemblies (FR2020 and FR2028) were exposed to standard (ISO 834) fires, while the furnace time-temperature relationship in the third test (FR2031) was intentionally modified to simulate more “severe” fire exposure. No information was provided with regard to furnace pressures. Each wall frame consisted of six cold-formed steel studs (spaced 600 mm o.c.) welded to top/bottom channels and bracing “nogs” at mid-height. “C”-shaped 76×32×1.15 mm studs (yield strength 300 MPa) were used in wall assembly

FR2020 (2.85 m high). The other two assemblies (of 3.6 m height) had lipped “C”-section studs with 102×51×1.0 mm dimensions and 450 MPa yield strength. The vertical seams between wall ends and the test frame were filled with fire resistant insulation. No wall cavity insulation was used in any of the assemblies. The steel frames were lined with a single layer of glass-fibre reinforced gypsum plasterboard on each side. These sheets were attached directly to the studs with self-drilling screws spaced at 300 mm o.c. The thickness of the gypsum board in wall assemblies FR2020 and FR2028 was 16 mm and 12.5 mm, respectively, on both sides. Assembly FR2031 had 12.5 mm thick board on the fire exposed side and 9.5 mm board on the ambient side. In all three tests, the external load was only applied to the four central studs. The load intensities were 6, 16 and 12 kN/stud in tests FR2020, FR2028 and FR2031, respectively. The tests were well instrumented and detailed information was provided with regard to measured temperatures and deflections. Vertical displacements of the loading platen indicated thermal expansion of the studs. In all tests, horizontal deflections were towards the furnace. The deflected shapes, based on horizontal deflection measurements along two central studs, suggested no significant rotational restraint at stud ends. Therefore, it was concluded that the end conditions for steel studs in a typical fire test set-up could be assumed to be hinged. The failure of all tested walls was governed by the structural collapse of loadbearing studs (generally, by buckling of the compression flange on the ambient side of the wall near mid-height) followed by the integrity failure of the unexposed gypsum board due to excessive deformations. The structural failures were observed at 72, 44 and 32 minutes in tests FR2020, FR2028 and FR2031, respectively.

The researchers noted that walls with low levels of axial load (such as FR2020) might perform better in fire tests than in actual fire situations because frictional restraints and redistribution of load can enhance the test result.

A recent experimental study on the fire resistance of steel stud walls (Kwon et al 1998) was conducted at the Fire Insurers Laboratories of Korea (FILK). In addition to tests on non-loadbearing LSF walls, four fire tests on two types of loadbearing exterior walls (wall-1 and wall-3) were described. The wall specimens were 3 m long by 2.4 m high, each framed with nine 140×40×1 mm lipped “C”-section steel studs (with “allowable stress” of about 300 MPa). The central seven studs were spaced 450 mm o.c. The load intensity was about 18.9 kN/stud. Rock wool insulation (140 mm thick) was used in all tests to fill wall cavities. Another unspecified insulation material, 10 mm thick, was used as the base lining layer on the “exterior” side of the four wall specimens. Type X gypsum board was used for all assemblies. It was attached to the vertical studs and horizontal tracks by screws spaced 300 mm o.c. Each of the two “exterior wall-1” specimens had two layers of local (produced in Korea) 12.5 mm thick gypsum board attached on both sides. These specimens were exposed to furnace fires from exterior and interior sides in two tests and exhibited structural failure at 28 and 40 minutes, respectively. The two “exterior wall-3” specimens, lined with one layer of imported (produced in Canada) 15.9 mm thick water-resistant gypsum board, were tested in a similar manner. In these tests, structural failures were observed at 25 minutes for exterior side fire exposure and at 30 minutes for interior side fire exposure. The investigators concluded that it was not possible to achieve a 1 hour rating for loadbearing LSF walls with a single layer of Type

X 15.9 mm thick gypsum board on each side. They also cited the fire retarding properties of the gypsum board as the major factor contributing to the fire resistance of steel stud walls. It was reported that three Korean manufacturers had developed new gypsum board products with improved fire protective characteristics. Loadbearing LSF walls lined with two layers of these newly-developed 12.5 mm thick gypsum boards on each side passed the requirements for a 1 hour fire resistance rating.

1.1. 6. Previous Analytical Studies

The earliest analytical method to predict the time of structural failure for loadbearing LSF walls subjected to standard fire was proposed by Klippstein (1978, 1980). The following basic assumptions were formulated:

- The gypsum board does not carry any vertical loads.
- The gypsum board prevents torsional buckling and weak axis (in the plane of the wall) buckling failure modes of the steel studs.
- Steel stress-strain relationships at elevated temperatures are linear up to the yield strength.
- The total vertical load applied to the wall assembly is always uniformly distributed among steel studs. The averaged axial load is applied concentrically to the steel stud section. The studs are hinged at the ends.
- All studs in the wall assembly experience equal temperature gradients, equal average temperatures and equal lateral deflections throughout the fire test. The temperature gradients and average temperatures are always uniform along the steel studs.

AISI allowable stress formulas (in effect at the time of the study), modified to account for the reduction of steel strength and stiffness at elevated temperatures, were used to estimate the load carrying capacity of the studs. The failure time was derived as a function of the “load ratio” and the thickness of gypsum board protection. The resulting load-time curves were presented for a number of generic wall assemblies. These curves are believed to be non-conservative for high load ratios (Gerlich 1995). Klippstein acknowledged the limitations of his method that was heavily dependent on “empirical” determination of stud temperatures and lateral deflections.

Gerlich (1995) employed a commercially available computer program, TASEF (Sterner and Wickstrom 1990), to model heat transfer through LSF walls exposed to fire. “Proprietary” (unspecified) thermal properties of gypsum board were used in the simulations. The numerical predictions showed good correlation with temperatures measured in three fire tests. TASEF was reported to yield somewhat non-conservative stud temperature predictions towards the end of the fire tests. These discrepancies were attributed to the degradation (opening of joints, cracking, ablation) of fire-exposed gypsum-board lining which caused an accelerated rise in measured temperatures, especially in test FR2031 simulating “severe” fire exposure. Gerlich (1995) used the same basic assumptions (listed earlier) formulated by Klippstein (1978) to analyze the structural behaviour of loadbearing LSF walls. The horizontal mid-height deflection of the studs was modelled as the sum of two components: stress-free thermal bowing deflection Δ_1 due to temperature gradient (assumed linear) across the steel stud section, and secondary deflection Δ_2 due to the average stud load P . The mid-height thermal

bowing deflection was treated as the initial eccentricity of the vertical load at stud ends (not at stud mid-height), and the following expression was derived for the secondary deformation (Gerlich et al 1996):

$$\Delta_2 = \Delta_1 \left[\left(\cos \sqrt{\frac{PL^2}{4E_T I}} \right)^{-1} - 1 \right] \quad (1.3)$$

where

$$\Delta_1 = \frac{\alpha_T L^2 \delta T}{8D} \quad (1.4)$$

Δ_1 and Δ_2 are in mm, P is in N

α_T = thermal expansion coefficient of steel in $^{\circ}\text{C}^{-1}$ at average stud temperature T

L = steel stud length in mm

δT = temperature difference across the depth of steel stud section in $^{\circ}\text{C}$

D = depth of steel stud section in mm

E_T = modulus of elasticity of steel in MPa at average stud temperature T

I = moment of inertia of the stud cross-section in mm^4

In numerical simulations, the values of Δ_1 (calculated using Equation 1.4) were assumed to remain constant when δT decreased. This was achieved by not allowing the calculated value of the thermal bowing deflection at any given time step to be less than in the previous step. The total horizontal deflection Δ at stud mid-height was calculated by adding the thermal bowing deflection to the secondary deflection calculated using Equation 1.3. The studs were then analyzed as steel members subjected to axial load P and bending moment $P\Delta$. A spreadsheet was developed based on AISI equations (Load

1991) adjusted to account for the reduction of steel strength and stiffness at elevated temperatures. An iteration procedure was used to determine critical temperatures, at which predicted steel stud capacities were equal to P . These critical temperatures were then compared with compression flange temperature histories to find the failure times.

Gerlich (1995) reported the horizontal deflections calculated from measured temperatures to agree well with measured mid-height deflections. Failure time predictions were most accurate when based on measured temperatures. The thermal model, however, was reported to predict greater than measured temperature differences across steel stud sections. Therefore, calculated lateral deflections based on TASEF temperatures overestimated the actual mid-height deflections measured in the fire tests. This effect resulted in slightly conservative failure time predictions within 80-90% of the test results.

Recently, extensive research efforts have been undertaken at the Fire Risk Management Program (FRM) of the Institute for Research in Construction (IRC) of the National Research Council of Canada (NRC) to develop reliable heat transfer numerical models for gypsum board cavity walls. Sultan (1996) presented a detailed description of a one-dimensional heat transfer model for non-insulated LSF walls. The model predictions showed promising correlation with temperatures measured in two fire tests (Sultan 1996, Sultan et al 1994) on non-load-bearing wall assemblies. The same experimental data was used to verify similar numerical simulations conducted by Cooper (1997).

1.2. Literature Review on Material Properties at Elevated Temperatures

The thermo-physical and mechanical properties of most materials change substantially within the temperature range associated with building fires. In the field of fire science, applied materials research faces numerous difficulties. At elevated temperatures, many building materials undergo physicochemical changes. Most of the properties are temperature dependent and sensitive to testing method parameters such as heating rate, strain rate, temperature gradient, etc. Harmathy (1983) cited the lack of adequate knowledge of the behaviour of building materials at elevated temperatures as the most disturbing trend in fire safety engineering. There has been a tendency to use “national” (“typical”, “proprietary”, “empirical”, etc.) values for material properties in numerical computations, in other words, values that ensure agreement between experimental and analytical results. Harmathy warned that this practice might lead to a proliferation of theories that lack general validity.

1.2.1. Steel

Steel starts losing its strength and stiffness at 100-250°C and eventually melts at about 1500°C. The mechanical properties of steel at elevated temperatures are strongly affected by creep, i.e., both stress and temperature histories influence steel deformations. Therefore, a clear distinction is made between isothermal “steady-state” tests and anisothermal “transient” tests (Anderberg 1983). Test regimes could also be either stress-rate or strain-rate controlled. Small steel specimens, similar to those used in standard room temperature tests, are usually tested in tension, and it is generally assumed that steel

stress-strain relationships in compression would be identical to those in tension. Transient tests usually produce more conservative results than steady-state tests, and they are considered to be more realistic with regard to building fire conditions.

Using data (Klippstein 1978, 1980) from several steady-state tests on cold-formed steel tension coupons (cut from studs), Gerlich (1995) derived the following expressions for temperature dependent yield strength F_{yT} (MPa) and modulus of elasticity E_T (for the temperature range below 650°C):

$$F_{yT} / F_y = 1.0 - 5.3 \cdot 10^{-4} T + 4.0 \cdot 10^{-6} T^2 - 1.9 \cdot 10^{-8} T^3 + 1.7 \cdot 10^{-11} T^4 \quad (1.5)$$

$$E_T / E = 1.0 - 3.0 \cdot 10^{-4} T + 3.7 \cdot 10^{-7} T^2 - 6.1 \cdot 10^{-9} T^3 + 5.4 \cdot 10^{-12} T^4 \quad (1.6)$$

where

T = steel temperature in °C

F_y = yield strength of steel in MPa at room temperature

E = modulus of elasticity of steel in MPa at room temperature

Makelainen and Miller (1983) conducted steady-state and transient tests on cold-formed galvanized sheet steel Z32. A comparison of results of steady-state tests conducted at high (3.5 MPa/s) and low (0.35 MPa/s) loading rates showed that creep effects become significant at 400°C and higher temperatures. It was also shown that the effect of zinc coating on the mechanical properties of steel is of little significance. The following expression was derived based on steady-state tests at high loading rate:

$$E_T / E = -0.46 \tanh[(T - 550) / 250] + 0.56 \quad \text{for} \quad 20^\circ\text{C} \leq T \leq 800^\circ\text{C} \quad (1.7)$$

Transient test results were approximated by:

$$F_{yT} / F_y = 1.088 - 0.1314 \exp[0.0047(T - 148.3)] \quad \text{for} \quad 20^\circ\text{C} \leq T \leq 500^\circ\text{C} \quad (1.8a)$$

$$F_{yT} / F_y = 104(1.0 - T/1135)/(T - 356) \quad \text{for } 500^\circ\text{C} \leq T \leq 800^\circ\text{C} \quad (1.8b)$$

$$E_T / E = 1.01 - 0.139\exp[0.007(T - 346)] \quad \text{for } 20^\circ\text{C} \leq T \leq 600^\circ\text{C} \quad (1.9)$$

The values of F_{yT} in Equations 1.5 and 1.8 are based on standard 0.2% offset stress values derived from elevated-temperature stress-strain curves. BS 5950 (1990) adopted a different approach (European 1983, European 1995) that defined higher effective yield strain limits (and corresponding higher strength values) for steel at elevated temperatures. BS 5950 suggests three sets of strength retention factors, F_{yT} / F_y , for galvanized cold-formed steel corresponding to 0.5%, 1.5% and 2% strains. These factors are illustrated in Figure 1.3 (along with Equations 1.5 and 1.8). They are based on anisothermal test results (Sidey and Teague 1988) statistically treated to accommodate the scatter. Therefore, BS 5950 curves represent a conservative 95% confidence limit (i.e. 5% chance that strength would fall below the curve), while Equations 1.5 and 1.8 are representative of mean test data. It should also be mentioned that F_y values used to derive BS 5950 curves correspond to the nominal (minimum specified) yield strength rather than to the actual yield strength of the steel tested. All transient tests mentioned (Makelainen and Miller 1983, Sidey and Teague 1988) were conducted at a heating rate of $10^\circ\text{C}/\text{min}$. Equations 1.6, 1.7 and 1.9 are compared in Figure 1.4. The modulus E_T represents the tangent modulus at low stress levels (or the initial tangent modulus), because steel stress-strain relationships become increasingly non-linear at elevated temperatures.

Steel expands when heated, and significant stresses may develop rapidly (at a rate of about $2.5 \text{ MPa}/^\circ\text{C}$) in a steel member if its thermal expansion is restrained. Elongation and thermal bowing of steel members in fire conditions may be significant. For the

temperature dependent thermal expansion coefficient of steel in Equation 1.4, Gerlich (1995) used the following expression (Lie 1992):

$$\alpha_T = (0.004 T + 12) \cdot 10^{-6} \quad (1.10)$$

which suggests that the thermal elongation strain ε_T of a steel member heated from the initial temperature of 20°C could be expressed as

$$\varepsilon_T = 0.2 \cdot 10^{-8} T^2 + 1.2 \cdot 10^{-5} T - 2.408 \cdot 10^{-4} \quad (1.11)$$

Lawson and Newman (1990) suggest an approximate constant α_T value of $14 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$ for use in simple models in the temperature range of 200 to 600°C ($12 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$ at room temperature). They also provide an expression for the thermal elongation strain ε_T of steel:

$$\varepsilon_T = 0.4 \cdot 10^{-8} T^2 + 1.2 \cdot 10^{-5} T - 2.416 \cdot 10^{-4} \quad \text{for} \quad 20^\circ\text{C} \leq T \leq 725^\circ\text{C} \quad (1.12)$$

Makelainen and Miller (1983) measured the thermal expansion strain ε_T of cold-formed galvanized steel in two transient tests on unloaded specimens and proposed the following equations:

$$\varepsilon_T = 0.5 \cdot 10^{-8} T^2 + 0.8 \cdot 10^{-5} T - 0.95 \cdot 10^{-3} \quad \text{for} \quad 200^\circ\text{C} \leq T \leq 500^\circ\text{C} \quad (1.13a)$$

$$\varepsilon_T = 2.0 \cdot 10^{-8} T^2 - 0.7 \cdot 10^{-5} T + 2.8 \cdot 10^{-3} \quad \text{for} \quad 500^\circ\text{C} \leq T \leq 600^\circ\text{C} \quad (1.13b)$$

As shown in Figure 1.5, these expressions suggest a somewhat lower thermal expansion of cold-formed steel when compared to Equations 1.11 and 1.12 for other steels.

The accurate determination of thermo-physical properties of steel, such as specific heat C_s and thermal conductivity k_s , is of little importance for the thermal modelling of LSF walls exposed to fire because steel framing plays a minor role in the heat transfer

mechanism. For most calculations, approximate constant values of $C_s = 0.52 \text{ kJ/(kg}^\circ\text{C)}$ and $k_s = 37.5 \text{ W/(m}^\circ\text{C)}$ have been suggested as alternatives to more accurate expressions (Lawson and Newman 1990):

$$C_s = 0.47 + 2.0 \cdot 10^{-4} T + 38 \cdot 10^{-8} T^2 \text{ (kJ/(kg}^\circ\text{C)) for } 20^\circ\text{C} \leq T \leq 725^\circ\text{C} \quad (1.14)$$

$$k_s = 52.57 - 1.541 \cdot 10^{-2} T - 2.155 \cdot 10^{-5} T^2 \text{ (W/(m}^\circ\text{C))} \quad (1.15)$$

The variation of the specific heat and the thermal conductivity of steel with temperature, according to Equations 1.14 and 1.15, is illustrated in Figures 1.6 and 1.7, respectively.

1.2.2. Gypsum Board

Gypsum board consists of a noncombustible core of not less than 65% gypsum (CAN/CSA-A82.27-M91) and paper laminated surfaces to form flat sheets available in a range of sizes. Special fire-resistant types of gypsum board are usually used for fire-rated loadbearing LSF walls. Type X 15.9 mm thick board and Type C 12.7 mm thick board are the fire-resistant products most widely used in Canada. Type C 15.9 mm thick board is also used in some designs. These products have a specially formulated gypsum core in order to provide a greater fire resistance (of building systems) than regular gypsum board of the same thickness.

Type X gypsum board is defined (CAN/CSA-A82.27-M91, ASTM C36-97) as the board that would provide the following minimum fire resistance ratings for the assemblies described:

- One hour for a non-load-bearing LSF wall with galvanized 92×35×0.5 mm steel studs spaced 600 mm o.c. and a single layer of 15.9 mm thick gypsum board on each side.

The 1200 mm wide gypsum board sheets should be attached to the studs using 25 mm long drywall screws spaced 200 mm o.c. along edges and ends, and 300 mm o.c. along intermediate studs. All joints should be oriented parallel to, and located over, studs and staggered on opposite sides of the assembly.

- Two hours for a non-load-bearing LSF wall with galvanized 64×35×0.5 mm steel studs spaced 600 mm o.c. and two layers of 12.7 mm thick gypsum board on each side. The gypsum board sheets should be 1200 mm wide. The base layer sheets should be attached to the studs using 25 mm long drywall screws spaced 300 mm o.c. along board edges, ends, and along intermediate studs. Base layer joints should be oriented parallel to, and located over, studs and staggered on opposite sides of the assembly. The face layer sheets should be attached using 41 mm long drywall screws spaced 300 mm o.c. along board edges, ends, and along intermediate studs. Face layer joints should be oriented parallel to, and located over, studs, offset 600 mm from base layer joints, and staggered on opposite sides of the assembly.

It should be mentioned that attachment details (screw spacing, orientation of gypsum board joints, stud spacing, etc.) can have a noticeable effect on the fire performance of the gypsum board. For example, NBCC Table A-9.10.3.1.A assigns only 45 minute and 1.5 hour ratings to non-loadbearing steel stud wall configurations S4c and S3i (respectively). These configurations are similar to those in the performance definition of Type X, but have slightly relaxed fastener spacing details as specified in CSA-A82.31.

Type C gypsum board does not have an associated product standard. Type C products are advertised by gypsum board manufacturers as exhibiting superior fire performance

characteristics (compared to Type X products) and exceeding the CSA and ASTM requirements for Type X gypsum board. However, it should be mentioned, that the wording “Type C” is rarely found in the designation of these products, but the letter “C” itself is often used (e.g. “Firecode C Core”, etc.).

Gypsum (calcium sulphate) dihydrate, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, the major component of the gypsum board core, contains chemically bound water of crystallization (about 21% by weight) in addition to a small amount of free moisture. The fire retarding property of gypsum board products derives primarily from this water content. When the gypsum board is exposed to fire, the water of crystallization is gradually released and evaporated, consuming large amounts of energy in the process and delaying heat transmission through the board. Therefore, gypsum board effectively acts as a fire barrier until most of its water content is driven out. As shown in Figure 1.1, the temperature of the protected steel studs directly behind the fire-exposed gypsum board remains around the boiling temperature of water (100°C) for the duration of the delay. The dehydration (release of water of crystallization) of gypsum dihydrate proceeds in two phases. The first phase, known as calcination, is associated with the formation of gypsum hemihydrate (semihydrate), $\text{CaSO}_4 \cdot 1/2\text{H}_2\text{O}$, at temperatures in the range of $80\text{--}150^\circ\text{C}$. The second phase of dehydration occurs at higher temperatures when the gypsum hemihydrate is transformed to gypsum anhydrite, CaSO_4 . In the case of fire near gypsum products, calcination of the core starts at the fire-exposed surface and penetrates through the thickness of the board. The progress of calcination is retarded by the layer of calcined gypsum on the fire-exposed surface, which adheres well to the inner uncalcined layers. Axenenko and Thorpe (1996) modelled the heat transfer

through gypsum board as a consequent movement of two dehydration fronts, associated with the two phases of dehydration.

The thermo-physical properties (Alexander 1982, Mehaffey et al 1994, Sultan 1996) of the gypsum board vary depending on the composition of the core. Figures 1.8 and 1.9 illustrate the typical variation of the specific heat and the thermal conductivity, respectively, of the gypsum board core with temperature. The plots reflect the expressions proposed by Sultan (1996) based on tests conducted on Type X gypsum board specimens. Specific heat measurements were carried out at a heating rate of 2°C/minute. The dehydration of gypsum resulted in the two peaks that appear in the specific heat curve at temperatures around 100°C and 650°C.

The Gypsum Association (Gypsum 1998) lists typical mechanical properties, at room temperature, for some North American gypsum board products. Little is known about the mechanical properties of the gypsum board at elevated temperatures because these properties are difficult to obtain experimentally. It should be mentioned, however, that the tensile strength and ductility of the gypsum board have a significant effect on its performance in fire. Gypsum board shrinks significantly (about 1.5% by the time it reaches 600°C) at elevated temperatures (Alexander et al 1982). When this shrinkage is restrained, considerable tensile stresses build up in the board, causing cracks within the field of the board and/or failure of the attachment connections. In LSF walls, the situation is further complicated by the elongation of heated steel studs. In order to remain in place, the gypsum board must possess tensile ductility sufficient to accommodate its thermal strain incompatibility with steel studs.

Even dehydrated gypsum board acts as a shield against fire flames and associated radiation emissions. The enhanced fire performance of Type X and Type C products derives primarily from their improved ability to stay in place for an extended period of time. This improved ability is usually achieved through reduced shrinkage and increased strength and ductility characteristics of the gypsum core. Special additives are used in the proprietary formulations of fire resistant boards to reduce their shrinkage (clay and vermiculite are often used) at elevated temperatures. Reinforcement fibres (usually glass fibres) are added to improve the mechanical properties of the boards. Type X and Type C products are usually of higher density than regular gypsum board.

1.2.3. Insulation

Mineral wool and glass fibre batts are the two insulation materials most widely used in combination with LSF assemblies. Exterior walls would normally be thermally insulated, whereas interior walls may contain insulation in order to meet sound transmission requirements.

The mineral wool insulation, when installed tight between the studs, can be beneficial for the fire resistance of non-loadbearing steel stud walls as it acts as an additional fire barrier after the fire-exposed gypsum board falls off (Sultan 1995). Glass fibre melts at about 700°C and cannot withstand direct fire exposure (Sultan and Lougheed 1994). It usually has neutral effect on the fire resistance of non-loadbearing LSF walls. Cavity insulation slows down the flow of heat through the wall assembly and can cause an

accelerated temperature rise in the fire-exposed gypsum board (Sultan and Loughheed 1994).

1.3. Recent Tests Conducted at FRM

Kodur et al. (1999) reported the results of three fire resistance tests on loadbearing LSF walls conducted recently at FRM of IRC/NRC. A detailed description of these tests is presented here because the data from these experiments will be used for comparative purposes and as a benchmark for numerical simulations presented in this research thesis.

The purpose of these three tests was to establish fire resistance ratings for generic loadbearing LSF walls with cavity insulation and resilient channels, and also, generate experimental data that would be useful for analytical studies. Various types of cavity insulation and resilient channels are often used in wall designs to improve their sound transmission classification (STC) ratings. However, little was known about the effect of insulation and resilient channels on fire resistance of loadbearing LSF walls.

The tests were conducted in accordance with the requirements of CAN/ULC-S101 in every detail. However, the hose stream tests (according to Clauses 7.3.3 and 5.2.2 of CAN/ULC-S101) were not conducted.

1.3.1. Wall Specimens

The wall assemblies tested (designated as W1, W2 and W3) were 3048 mm high, 3658 mm long and 157 mm deep. Each assembly consisted of a single row of galvanized cold-

formed steel studs, protected with two layers of fire resistant gypsum board on each side.

Table 1.1 provides a summary of the variable parameters of the wall specimens.

The lateral stability of the steel stud frames in the plane of the wall was provided by top and bottom channel tracks, diagonal cross-bracing, two rows of bridging and solid blocking in four locations, designed in accordance with S136-94. Galvanized steel straps were used for cross-bracing and bridging, while the blocking was fabricated from channel track sections. The steel frame members were connected to each other at every intersection by 19 mm long self-drilling wafer head screws. Figure 1.10 illustrates the steel frame fabrication layout for wall assemblies W1 and W3. Each of these frames had ten loadbearing studs spaced 406 mm o.c. The steel frame for wall specimen W2 had only seven studs spaced 610 mm o.c., but had a similar fabrication layout in terms of top/bottom tracks, bridging, cross-bracing and blocking.

Figure 1.11 illustrates the cross-sectional details of the wall specimens. All steel studs had a C-shaped cross-section, 92.1 mm deep by 41.3 mm wide, with 12.7 mm stiffening lips. The studs were fabricated from galvanized steel sheets having a nominal base metal thickness of 0.912 mm, minimum specified yield strength of 230 MPa and ultimate tensile strength of 310 MPa. Control measurements showed an average base metal thickness under-run of 0.01 mm, which is within specified limits (Sheet 1998). Each stud had four web perforations, 38 mm wide, spaced 610 mm o.c. along the stud length.

Nine resilient channels, spaced 406 mm o.c., were attached perpendicular to the studs on the fire-exposed side of each frame. The resilient channels, 14 mm deep and 58 mm wide, were fabricated from 0.6 mm thick galvanized steel sheets. The channels had a 30 mm

wide web, designed to support the gypsum board connections, and a 15 mm wide flattened flange lip, connected to the steel studs by 19 mm long self-drilling wafer head screws.

The gypsum board used in all tests had the “Firecode C Core Type X” designation implying that it met and exceeded the requirements of CAN/CSA-A82.27 and ASTM C36 for Type X gypsum board. The board had a nominal thickness of 12.7 mm and a bulk density of 750 kg/m³. It was supplied in 1219 mm wide sheets, 3048 mm and 3658 mm long. The installation of the gypsum board was conducted in accordance with CAN/CSA-A82.31. The boards on the unexposed side were applied vertically and attached to the steel studs. The base layer boards were attached by 32 mm long self-drilling drywall screws spaced 305 mm o.c. along edges, and 610 mm o.c. along intermediate studs. Base layer joints were oriented parallel to, and located over, studs. The face layer boards were attached by 41 mm long self-drilling drywall screws spaced 305 mm o.c. along edges and intermediate studs. Face layer joints were oriented parallel to, and located over, studs and offset 406 mm (610 mm in the case of W2) from base layer joints. Figure 1.12 illustrates the installation of gypsum board on the unexposed side of specimen W1.

The gypsum boards on the fire-exposed side were oriented horizontally and attached to the resilient channels. The base layer boards were attached by 32 mm long Type S drywall screws spaced 305 mm o.c. along edges, and 610 mm o.c. along intermediate resilient channels. The edge joints of these boards were oriented parallel to, and located over, resilient channels. The face layer boards were attached by 41 mm long Type S

drywall screws spaced 305 mm along edges and intermediate resilient channels. The edge joints of face layer boards were oriented parallel to, and located over, resilient channels and offset 406 mm from base layer edge joints. Figures 1.13 and 1.14 illustrate the layout of the base and face gypsum board layers, respectively, on the fire-exposed side. As shown in these figures, there was a 1219 mm long unsupported vertical joint in the base layer, and a similar 812 mm long vertical joint in the face layer.

All drywall screw heads were covered with two applications of joint compound. All gypsum board joints were taped and covered with two applications of joint compound.

Three different types of insulation, all meeting the requirements of CAN/CSA-A101, were used in this test series, namely, glass fibre (with bulk density of 10 kg/m^3), rock fibre (33 kg/m^3) and dry blown cellulose (47 kg/m^3). Glass fibre batts, 92 mm thick, 1219 mm long and 406 mm wide, were placed between the studs of wall assembly W1. Wall specimen W2 was insulated with rock fibre batts, 89 mm thick, 616 mm wide and 1256 mm long. The cellulose insulation was dry-blown into the wall cavity of specimen W3. For the purpose of cellulose insulation placement, the cavity was formed, after the installation of the gypsum board on the unexposed side of the wall, by the attachment of a polypropylene mesh to the steel studs on the fire-exposed side of the steel frame (the mesh formed a vertical plane between the studs and resilient channels).

1.3.2. Test Setup and Instrumentation

The wall specimens were tested in the propane-fired wall furnace of NRC. The details of the furnace and the loading frame are described elsewhere (Shorter and Harmathy 1960).

The specimens were placed on a rigid steel beam base against the vertical furnace. Two reinforced concrete posts, fixed in place at a clear distance of 3680 mm from each other, formed the vertical boundaries of the wall specimen holder. A clear space, about 10 mm wide, was provided between these posts and the ends of wall specimens in order to avoid any restraint action on the vertical edges of the specimens, in accordance with CAN/ULC-S101. During the installation of wall assemblies, special attention was given to the proper alignment of all test setup components.

The vertical load was applied at the top of wall specimens by eight hydraulic actuators (127 mm in internal diameter, maximum stroke of 152 mm), spaced 406 mm o.c., through a rigid steel beam. The load spreading steel beam, 3580 mm long, was connected to the hydraulic actuators via eight multidirectional swivels. However, a specially designed system restricted the rotation of the loading beam about the longitudinal axis (an axis passing through the rotational centres of all swivels). In order to minimize heat transfer to the loading system during fire tests, a wooden header, 39 mm thick, was attached to the top channel track of each wall assembly, as shown in Figure 1.10. This wooden header also served load transfer to the studs at wall ends, since the load spreading beam was slightly shorter than the tested specimens.

Joints along the perimeter of the fire exposed side of the wall assemblies, critical parts of the specimen holder frame and the loading system, including the loading beam and the wooden header, were protected on the furnace side by ceramic fibre blankets. These ceramic fibre blankets were extended to cover about 75-mm wide strip along the perimeter of the wall specimens.

A single pump supplied the hydraulic pressure to all loading actuators. The total load was controlled by adjusting the hydraulic pressure in the feeding line. Prior to the beginning of this experimental program, the hydraulic loading system was appropriately calibrated using load cells. During the tests, the load was incrementally applied to the specimen up to the desired level and then held constant at this level for about 45 minutes before furnace ignition and throughout the fire endurance test. The total vertical load applied to specimens W1 and W3 was 73.3 kN, and the load applied to specimen W2 was 46.8 kN. These loads were meant to simulate the restricted loading condition, corresponding to about 92% of the maximum service load allowed by structural design criteria. The maximum service load was derived based on the factored resistance of a single steel stud in axial compression $C_r = 13.8$ kN, according to the provisions of S136-94, divided by the load factor of 1.45, assuming a live to dead load ratio of 4. The resulting value was transformed to maximum line loads of 23.4 kN/m (for specimens W1 and W3) and 15.6 kN/m (for specimen W2), which are supposed to include wall self-weight in addition to the applied load.

In accordance with standard test procedures, the temperatures in the furnace were measured by nine (20 gauge) shielded thermocouples, installed at appropriate locations. The furnace was automatically adjusted so that the average temperature from these thermocouple measurements, deemed to represent the furnace temperature, closely followed the standard time-temperature relationship. A slight negative furnace pressure (around -30 Pa at the bottom probe and neutral at the top probe) was maintained during the tests.

All other temperature measurements were conducted using Type K chromel-alumel thermocouples, 0.91 mm thick. Nine thermocouples were placed under standard pads on the unexposed side of the wall in each test. The temperatures measured from these thermocouples were meant to indicate the heat penetration failure (if any) of the specimens, according to the standard criteria (a single point temperature rise of 180°C, or an average temperature rise of 140°C). Although not required by the test standard, another six thermocouples, without pads, were also placed on the unexposed surface of each specimen.

In order to generate experimental data for heat transfer analytical studies, numerous locations within the structure of the wall specimens were also instrumented with thermocouples. In each assembly, these were arranged in two groups, symmetric about a horizontal plane at the mid-height of the wall, at two elevation levels: 762 mm from the bottom of the wall (0.25 H level, where H = wall height = 3048 mm) and 2286 mm from the bottom of the wall (0.75 H level). Most of the thermocouples were distributed within the central part of the wall specimens, about 2 m long, at the following generalized locations, as illustrated in Figure 1.11:

- between the face and base layers of gypsum board on the exposed side of the wall (generalized locations 1a and 1b, 10-12 thermocouples per assembly),
- on the exposed side surface of the exposed side flanges (hot flanges) of the steel studs at the middle of the flange width (generalized location 2a, 4-6 thermocouples per assembly),

- on the cavity-facing surface of the base layer of the gypsum board, on the exposed side of the wall, midway between neighbouring studs (generalized location 2b, 6 thermocouples per assembly),
- on the webs of steel studs at the middle of the stud depth (generalized location 3, 4 thermocouples per assembly),
- between steel studs and the base layer of the gypsum board on the unexposed side (generalized location 4a, 4-6 thermocouples per assembly),
- on the cavity-facing surface of the base layer of the gypsum board on the unexposed side, midway between neighbouring studs (generalized location 4b, 6 thermocouples per assembly), and
- between the base and face layers of the gypsum board on the unexposed side (generalized locations 5a and 5b, 10-12 thermocouples per assembly).

In addition, each of the wall end studs in assemblies W2 and W3 was instrumented with two thermocouples at each of the hot flange (2a) and cold flange (4a) generalized locations.

The horizontal deflections of the wall specimens were measured by potentiometers (Lie and Berndt 1972) on the unexposed side, at nine locations in each test. These measurements were taken at three elevation levels (0.25 H, 0.5 H and 0.75 H levels) at three studs in the central part of the wall specimen. The horizontal deflections were measured at studs 3, 6 and 8 in tests W1 and W3, and at studs 2, 4 and 6 in test W2 (the studs are numbered in sequence starting with the first stud at the east end of the wall

specimen). Two displacement transducers measured the vertical movement of the loading beam during tests W2 and W3.

All measured temperatures, displacements and pressure in the furnace and the hydraulic loading system were recorded electronically by a data acquisition system at 1 minute intervals. Every test was also recorded by three video cameras. One of them recorded the view of the unexposed side of the wall specimen, while the other two recorded the view of the fire exposed side from two observation ports in the side walls of the furnace.

1.3.3. Observations and Results

A short summary of test results is provided in Table 1.1. According to conditions of acceptance (CAN/ULC-S101), the wall specimens failed by losing their ability to sustain the applied load. The loss of the loadbearing function (structural failure) in all tests occurred before heat penetration failure on the unexposed side took place. The structural failure time is the number of full minutes passed since the ignition of the furnace before the loss of the loadbearing function. In all tests, the structural failure proceeded in a rather abrupt manner, resulting in the overall out-of-plane buckling of the walls in the direction away from the furnace. Passage of flames and hot gases to the unexposed side immediately followed the structural failure.

In all tests, fall-off of the gypsum board on the fire-exposed side of the specimens was observed several minutes prior to structural failure. The fall-off times shown in Table 1.1 indicate the number of full minutes passed since the ignition of the furnace before the fall-off of a gypsum board layer piece not less than 500 mm in any dimension. The base

layer gypsum board on the exposed side of wall assemblies W1 and W3 remained in place until the end of the test.

After each test, all gypsum board on the fire-exposed side was removed and a visual observation of wall assembly components was conducted. The fibre glass insulation in wall W1 remained almost intact, with signs of limited local deterioration at several locations on the furnace side of the batts. The rock fibre insulation in assembly W2 also remained in fairly good condition, even the batts in the central part of the wall, which were exposed to direct furnace flames for several minutes. In the case of assembly W3, no remains of the polypropylene mesh were found (it looked as if it had completely burned out). The cellulose insulation was completely filling the cavities between studs, except two cavities where about 200 mm settlement of the loose-fill cellulose occurred. A clear boundary between white (original colour) and black (due to heat exposure) cellulose was observed at about 10 mm from the base layer of gypsum board on the unexposed side. In all three assemblies, the cavity-facing paper surface of the base layer gypsum board on the unexposed side was almost intact, with few signs of local charring. Inspection of other surfaces of the gypsum boards on the unexposed side showed no visible signs of deterioration due to heat in any of the tests.

The deformed shapes of the steel studs were inspected after each test in order to determine the structural failure modes. In test W3, all ten studs exhibited compressive failure (local buckling) of the hot flange at the location of the first perforation (about 0.2 H level, counting from the bottom of the wall). Figure 1.15 illustrates the steel frame of specimen W3 after the fire test. The same failure mode was observed in the six central

studs of assembly W1. The other four studs (two at each wall end) of specimen W1 exhibited similar compressive failure of the hot flange at the second perforation (about 0.4 H level).

The west end stud of wall specimen W2 remained undamaged. The east end stud of this wall failed in compression on its entire section just below the upper track. Each of the remaining five studs in the central part of the wall had two failure locations: at the first perforation (about 0.2 H level), and at the fourth perforation (about 0.8 H level). Both locations exhibited compressive failure of the hot flange. A clear double-curved shape of the unexposed surface of assembly W2 was observed during the last several minutes of the test, prior to failure, with the upper part of the wall curved towards the furnace, and the lower part curved away from the furnace. Therefore, since it is not likely that the central studs failed at two locations simultaneously, it is believed that the failure at the lower location (first perforation) occurred first.

The average temperatures measured in the central part of the wall assemblies are illustrated in Figure 1.16. Average hot flange temperatures just prior to structural failure were about 550°C, 800°C and 650°C for specimens W1, W2 and W3, respectively. Temperatures measured on the unexposed surface of the wall specimens are not shown in the figure, as these temperatures were very low.

The plots of the average lateral deflections measured in the central part of the wall assemblies are presented in Figure 1.17. Positive horizontal deflections indicate movement towards the furnace. These reflect the thermal bowing and secondary deformations of the steel studs caused by the development of temperature gradients

between the hot and cold flanges. In all three plots, the lateral deflection curves for the 25% wall height level are distinctive from the other two curves, showing an early reversal in the development of the positive lateral deflection. These reversals are consistent with the structural failure modes observed. In all tests, large negative (away from furnace) lateral deflections were recorded at all wall height levels after the structural failure (these are not shown on the plots in order to maintain an appropriate scale of the plots).

Vertical displacements recorded during tests W2 and W3 (see Figure 1.18) indicated upward movement of the loading beam, consistent with the thermal expansion of the studs, followed by a gradual downward movement during the last few minutes prior to structural failure.

The lateral deflection at the ends of the wall specimens was not measured in any of the tests. However, it was visually observed in all tests that the bowing of the end studs was considerably less than that of the studs in the central part of the assemblies. This observation is consistent with the temperature data recorded from thermocouples installed at the end studs. Figure 1.19 shows the average hot flange and cold flange temperatures measured at the end studs of assembly W2 compared to respective average temperatures in the central part of the specimen. The temperature data from test W3 (Figure 1.20) also indicates that the end studs were heated much slower (and experienced smaller temperature gradients) than the central studs.

1.3.4. Discussion of Test Results

Since all tested assemblies exhibited structural failure, it was clear that loading plays a significant role in fire resistance tests. The temperature rise (both maximum and average) on the unexposed side of all assemblies was considerably (more than 100°C) below standard failure criteria by the end of the tests. This suggests that much higher fire resistance ratings are likely to be achieved in fire tests on similar non-loadbearing LSF assemblies.

The structural failure mode described by Gerlich et al (1996), i.e. the compressive failure of cold flange near stud mid-height with subsequent overall buckling towards the furnace, was not observed in any of the studs in this test series. This observation posed a question of which variations in specimen configurations and test arrangements had caused the different behaviour observed.

The positive peaks in the 0.25 H lateral deflection curves of Figure 1.17 indicate the beginning of stud movement away from the furnace. It is likely that they reflect the initiation of the local compressive failure of the hot flange at the first perforation (about 0.2 H level).

It can be observed, from the time-temperature curves of Figure 1.16, that two layers of 12.7 mm thick fire resistant gypsum board provided about 40 minutes of delay in the temperature rise in the hot flanges. The duration of this delay seems to be insensitive to the type of insulation used in the wall assembly. The temperature rise in steel studs after that was the fastest in wall W1 with glass fiber insulation, and the slowest in wall W3 with cellulose fiber insulation. This correlates somewhat with the lower bulk density (and

associated lower thermal capacity) of the glass fiber insulation and the higher bulk density of the cellulose fibre insulation. There does not seem to be much difference between the temperature histories at generalized location 1 from the three tests. Therefore, it is not clear whether the type of insulation had any effect on the fall-off times of the face layer of gypsum board on the exposed side.

Heating of the central steel studs in test W2 proceeded faster than in test W3. This was not consistent with the fact that the fire resistance of specimen W2 was 3 minutes higher than the fire resistance of specimen W3. It appeared that the wider stud spacing in wall W2 (and the associated smaller total load applied to specimen W2) was beneficial for its fire resistance.

1.4. Summary of Background: Direction of Future Research

The current practice of establishing fire resistance ratings for loadbearing LSF walls is prescriptive and limited to a narrow choice from a few listed assemblies. There is a growing demand among related professionals for performance-based design methods. Development of such analytical methods would require a greater understanding of thermophysical and structural phenomena that occur in construction assemblies subjected to fire attack.

The established practice of confidentiality of fire endurance test results holds back the development of knowledge in fire safety engineering. Very little experimental data is available on the performance of loadbearing LSF walls exposed to fire. There is a need for a much broader experimental database. The research effectiveness of future test

programs could be substantially improved by using more instrumentation in fire resistance tests. Future experimental programs could also be substantially optimised by making use of the conventional research wisdom of combining experiment with analysis and numerical modelling.

Computational techniques are becoming increasingly important as research tools in structural fire protection because they provide engineers with a better understanding and interpretation of experimental results. The available numerical heat transfer models for non-insulated gypsum board cavity walls are capable of predicting temperatures with reasonable accuracy as long as the gypsum board stays in place. It is generally expected that future developments in numerical techniques will address cavity insulation and the fall-off of gypsum board. Previous analytical studies, with regard to the structural behaviour of loadbearing LSF walls exposed to fire, are based on numerous assumptions and involve rather crude approximations. More detailed experimental data would be necessary to confirm or depart from these assumptions and approximations. The non-uniformity of load distribution among studs, the end conditions of the studs, the concentricity of load application and the role of the gypsum board in the structural behaviour of LSF walls in standard fire tests are among the issues that require investigation.

1.5. Scope of Research Thesis Project

This research project consisted of three major parts, namely, a literature review, an experimental part and an analytical part. The first part included:

- review of literature pertaining to the fire resistance of loadbearing LSF walls,
- review of literature pertaining to the properties of materials at elevated temperatures,
- processing and analysis of raw experimental data from three FRM tests described in Section 1.3.

The experimental part of the project consisted of:

- processing and analysis of proprietary (currently not open for public) raw experimental data from ten standard fire resistance tests on LSF walls (eight loadbearing walls and two non-loadbearing walls), conducted earlier at FRM, with the purpose to identify characteristic patterns in thermal transmission and structural behaviour,
- identification of parameters that require experimental investigation,
- design and supervision of three additional standard fire resistance tests on loadbearing LSF walls,
- processing and analysis of raw experimental data from three additional tests.
- processing and analysis of raw experimental data from fire resistance tests on five unrestrained LSF floors (Sultan et al 1998),

The analytical part of the project consisted of:

- development of computer program TRACE for thermal simulations and computer program STUD for structural simulations,
- conduct of retrospective thermal (using TRACE) and structural (using STUD) numerical simulations of six fire resistance tests on loadbearing LSF walls, including calibration of necessary thermal and structural parameters,

- development of computer program JOIST for structural simulations of floor tests,
- conduct of retrospective thermal (using TRACE) and structural (using JOIST) numerical simulations of five fire resistance tests on unrestrained LSF floors, including calibration of necessary thermal and structural parameters.

The major findings of this research project were reported in several peer-reviewed papers presented at national and international conferences (Alfawakhiri and Sultan 1999, Kodur et al 1999, Alfawakhiri et al 2000, Alfawakhiri and Sultan 2000, Alfawakhiri and Sultan 2001). A review of the fire resistance of loadbearing steel stud walls was also published in the Fire Technology Journal (Alfawakhiri et al 1999).

Table 1.1. Summary of FRM Fire Resistance Tests on Loadbearing LSF walls.

Specimen number	Stud spacing (mm)	Insulation type (fibre)	Resilient channels on exposed side	Load including self-weight (kN/m)	Fall-off time of gypsum board on exposed side (min)		Structural failure time (min)	Temperature rise on unexposed side, under pads, at failure time (°C)	
					Face layer	Base layer		Maximum	Average
W1	406	Glass	Yes	21.5	50	in place	55	52	36
W2	610	Rock	Yes	14.3	57	67	73	50	42
W3	406	Cellulose	Yes	21.5	57	in place	70	42	37

Figure 1.1. Typical Temperature History of a Steel Stud within an LSF Wall.

Figure 1.2. Standard Time-Temperature Curves.

Figure 1.3. Reduction of Yield Strength of Cold-Formed Steel at Elevated Temperatures.

Figure 1.4. Modulus of Elasticity of Cold-Formed Steel at Elevated Temperatures.

Figure 1.5. Thermal Expansion of Hot-Rolled and Cold-Formed Steels.

Figure 1.6. Variation of the Specific Heat of Steel with Temperature.

Figure 1.7. Variation of the Thermal Conductivity of Steel with Temperature.

Figure 1.8. Specific Heat of Type X Gypsum Board Core.

Figure 1.9. Thermal Conductivity of Type X Gypsum Board Core.

Figure 1.10. Typical Steel Frame Fabrication Layout for Wall Specimens.

Figure 1.11. Locations of Temperature Measurements and Simulation Boundaries.

Figure 1.12. Gypsum Board Installation for Wall Specimen W1 (Unexposed Side).

Figure 1.13. Base Layer Gypsum Board Layout (Fire Exposed Side).

Figure 1.14. Face Layer Gypsum Board Layout (Fire Exposed Side).

Figure 1.15. Steel Frame of Wall Specimen W3 after Fire Test (Unexposed Side View).

Figure 1.16. Average Temperatures Measured during FRM Wall Tests.

Figure 1.16 (continued). Average Temperatures Measured during FRM Wall Tests.

Figure 1.17. Average Deflections Measured during FRM Wall Tests.

Figure 1.17 (continued). Average Deflections Measured during FRM Wall Tests.

Figure 1.18. Average Vertical Displacements of the Loading Beam Measured during FRM Wall Tests.

Figure 1.19. Average Temperatures Measured at Central and End Studs (Test W2).

Figure 1.20. Average Temperatures Measured at Central and End Studs (Test W3).

Chapter 2

Fire Resistance Tests

The experimental part of this research project consists of three standard fire resistance tests on loadbearing LSF walls that were designed to complement the earlier FRM tests, described in Section 1.3. The purpose of these tests was also to obtain additional detailed experimental data that would be useful for analytical and numerical studies.

The focus in the selection of the parameters for the three tests was to investigate effects that cannot be derived with certainty from the first principles. Detailed analysis of proprietary experimental data from previous tests indirectly suggested the following trends:

- Cavity insulation has a negative impact on the fire resistance of loadbearing LSF walls, mainly, because it reduces the ability of fire exposed gypsum board to remain in place.
- Wider stud spacing is beneficial for the fire resistance of loadbearing LSF walls because it reduces the total load applied during the standard test and amplifies the beneficial effect of load redistribution to the colder studs at wall ends.

- Resilient channels on the fire exposed side of the wall have a negative impact on the fire resistance of loadbearing LSF walls in standard tests because they reduce the ability of gypsum board to remain in place (as compared to the direct attachment of gypsum board to studs).

The three trends stated above were identified as factors that are likely to affect fire resistance significantly, but cannot be quantified analytically in a meaningful manner. In addition, these trends were in controversy with the following generally held beliefs:

- Insulation improves (or, at least, does not affect) fire resistance.
- Wider stud spacing reduces fire resistance (note, that listed designs usually limit stud spacing by a maximum value).
- Installation of resilient channels increases the depth of the wall cavity, and therefore, improves fire resistance.

It was proposed that the three trends be clearly established experimentally by direct comparison of two similar assemblies with the effect of only one parameter investigated at a time (i.e. with effect of other parameters separated). The following three tests were suggested:

- Test W4: duplicate of test W1, but without cavity insulation. This test was to establish the effect of cavity insulation on the fire resistance of loadbearing LSF walls.
- Test W5: duplicate of test W2, but with 406 mm o.c. stud spacing. This test was to establish the effect of stud spacing on the fire resistance of loadbearing LSF walls.
- Test W6: duplicate of test W4, but without resilient channels (i.e. with fire exposed gypsum board attached directly to studs).

2.1. Wall Specimens

Table 2.1 lists the various parameters for the tests. The wall specimens were constructed in a manner similar to that described in Section 1.3. In order to ensure comparable test results, the materials used in tests W4-W6 were identical to those used in tests W1-W3. The gypsum boards, attachment screws and rock fibre insulation used for tests W4-W6 were of the same type as those used in test W1-W3. The steel studs and resilient channels used for tests W4-W6 were from the same delivery as those used in test W1-W3.

2.2. Test Setup and Instrumentation

The wall specimens were tested in the propane-fired wall furnace at NRC. The loading arrangements, test setup and procedures were as described in Section 1.3. The tests were also extensively instrumented in a manner similar to the instrumentation of Tests W1-W3.

2.3. Observations and Results

A short summary of test results is provided in Table 2.1. All three wall specimens exhibited structural failure before any significant heat penetration to the unexposed side could occur. In test W5 the structural failure resulted in the overall out-of-plane buckling of the wall in the direction away from the furnace. In contrast to that, the structural failure in tests W4 and W6 resulted in the overall out-of-plane buckling of the walls in the

direction towards the furnace. Figure 2.1 schematically illustrates the observed structural failure modes.

In tests W4 and W5, fall-off of the gypsum board face layer on the fire-exposed side of the specimens was observed. The fall-off times in Table 2.1 reflect the beginning of gypsum board layer fall-off. In all cases, the fall-off occurred due to the deterioration of gypsum board around attachment screws (usually, starting at a corner, or at an end, or at an edge of a gypsum board sheet). Close inspection of wall assemblies after fire tests indicated that resilient channels remained properly attached to studs, and board attachment screws remained attached to resilient channels. In test W6, all the gypsum board on the fire-exposed side remained in place until the end of the test.

After each test, all the gypsum board on the fire-exposed side was removed and a visual observation of the wall assembly components was conducted. In tests W4 and W6, the cavity-facing surface of the base layer of gypsum board on the unexposed side was significantly charred and burned out. In test W5, it was completely intact, without any signs of charring. The rock fibre batts in this test remained almost intact, with the furnace-side surface having signs of limited local deterioration due to heat at several locations.

The deformed shapes of the steel studs were inspected after each test in order to determine the structural failure modes. In test W5, all the studs failed by compressive failure (local buckling) of the hot flange at web perforation locations. Studs 1,2, 9 and 10 failed at the second perforation (about 0.4 H level), while studs 3-8 failed at the first perforation (about 0.2 H level).

In test W4, studs 3-9 failed by compressive failure (local buckling) of the cold flange at the third perforation (about 0.6 H level) or midway between second and third perforations (between 0.4 and 0.6 H). Stud 10 failed by compressive failure (local buckling) of cold flange midway between third and forth perforations (between 0.6 and 0.8 H). Stud 2 failed by compressive failure (local buckling) of the cold flange at the fourth perforation (0.8 H). Stud 1 exhibited compressive failure of the entire section just below the upper track.

In test W6, studs 2-9 failed by compressive failure (local buckling) of the cold flange at the second or third perforation (0.4 or 0.6 H). Studs 1 and 10 in this test exhibited compressive failure of cold flange between third and fourth perforations (between 0.6 and 0.8 H).

Individual thermocouple and deformation gauge records for tests W4-W6 are presented in Appendix A. Figures 2.2-2.4 show histories of average temperatures, designated by respective generalized location numbers, measured in the central part of wall specimens. The average hot flange temperatures measured just prior to structural failure were about 530°C, 630°C and 550°C for specimens W4, W5 and W6, respectively. Temperatures, measured on the unexposed surface of the wall specimens are not shown in these figures, as these temperatures were low.

The plots of average lateral deflections are presented in Figures 2.5-2.7. Positive deflections indicate movement towards the furnace. Large lateral deflections were recorded at all elevation levels at the end of all tests, as structural failure resulted in the overall out-of-plane buckling of the walls. These large deflections are not shown on the

figures in order to maintain an appropriate scale of the plots. The 0.25 H level curve for test W5 in Figure 2.6 shows an early reversal in the development of the positive lateral deflection, similar to that observed in tests W1-W3. Such reversals are not observed in tests W4 and W6.

Vertical displacements recorded during tests W4-W6 (see Appendix A) indicated upward movement of the loading beam, consistent with the thermal expansion of the studs, followed by the downward movement during the last few minutes prior to structural failure.

Temperatures measured at hot and cold flanges of studs at wall ends indicated that these studs remained significantly cooler during the tests than the other (central) studs in wall assemblies. Figures 2.8-2.10 illustrate this trend by comparing the temperatures measured at the central and end studs.

2.4. Discussion

The following trends in the behaviour of loadbearing LSF walls, exposed to standard fire, have been established based on experimental observations and measured data:

- Heat penetration failure was not detected in any of the tests. All specimens failed by losing their ability to sustain the applied load (i.e. exhibited structural failure). As shown in Table 2.1, the temperature rise on the unexposed side was considerably (at least 70°C) below standard failure criteria by the end of the tests. This suggests that much higher fire resistance ratings are likely to be achieved in fire tests on similar non-loadbearing LSF assemblies (that usually fail due to excessive temperature rise

on the unexposed surface). Clearly, loading significantly reduces fire resistance of LSF walls.

- In all tests, two layers of 12.7-mm thick fire resistant gypsum board provided about 40 minutes of delay in the temperature rise in the hot flanges of the studs (generalized location 2a). The duration of this delay can be regarded as a stable property of the gypsum board used in the tests, as it seems to be insensitive to the parameters of this test series.
- Comparison of tests W1, W3 and W5 versus test W4 suggests that insulation placed in wall cavity reduces the fire resistance of loadbearing LSF walls.
- Insulation restricts the passage (and dissipation) of heat through the cavity causing an accelerated temperature rise in the hot flanges, and a delayed temperature rise in the cold flanges, of the studs. Therefore, the heating regime of studs in insulated walls features high temperature gradients across the steel section, while the heating regime of studs in non-insulated walls is rather close to uniform heating. The development of lateral deflections (thermal bowing) correlates well with the development of temperature gradients across the steel section.
- Structural failure resulted in overall buckling towards the furnace for non-insulated walls (tests W4 and W6) and away from the furnace for insulated walls (tests W1-W3 and W5). The dominant failure mode for studs in non-insulated walls was the compressive failure of the cold flange near mid-height, as illustrated in Figure 2.1a. The dominant failure mode for studs in insulated walls was the compressive failure of the hot flange at the location of the first web perforation (0.2 H level), as shown in

Figure 2.1b. This difference in observed structural behavior of steel studs in non-insulated and insulated walls can be attributed to the difference in heating regimes described above.

- **The positive peaks in the 0.25 H lateral deflection curves for insulated walls indicate the beginning of stud movement away from the furnace. They reflect the initiation of the failure mechanism in the central studs of insulated walls.**
- **The temperature rise at wall ends proceeded significantly slower than in the central part of the specimens, especially during tests on insulated walls. As a result, the end studs were subjected to smaller temperature gradients and exhibited smaller thermal bowing than the remaining studs in the central part of wall specimens. The structural failure modes of the end studs were usually different from the dominant failure modes of the central studs.**
- **Comparison of test W2 versus test W5 indicates that wider stud spacing is beneficial for the fire resistance of loadbearing LSF walls in standard tests. For a given service load per stud, wider stud spacing results in smaller total test load (due to fewer studs in the assembly). Since the wall specimens are loaded between rigid beams, the two colder studs at wall ends are largely responsible for resisting this total load during the final phase of the fire tests. Therefore, a reduction in total load significantly improved fire resistance in test W2. Contrary to generally held belief, wider stud spacing of loadbearing LSF walls should not be associated with a reduction in their fire**

resistance (especially, when the fire exposed gypsum board is not attached to studs directly).

- Comparison of test W4 versus test W6 suggests that installation of resilient channels, and the resulting horizontal orientation of gypsum board sheets, reduces the fire resistance of loadbearing LSF walls in standard tests, because it reduces the ability of fire exposed gypsum board to remain in place.

Table 2.1. Summary of Fire Resistance Tests on Loadbearing LSF Walls.

Specimen number	Stud spacing (mm)	Insulation type (fibre)	Resilient channels on exposed side	Load including self-weight (kN/m)	Fall-off time of gypsum board on exposed side (min)		Structural failure time (min)	Temperature rise on unexposed side, under pads, at failure time (°C)	
					Face layer	Base layer		Maximum	Average
W4	406	-	Yes	21.5	58	in place	76	64	60
W5	406	Rock	Yes	21.5	53	in place	59	37	26
W6	406	-	No	21.5	in place	in place	83	76	69

Figure 2.1. Structural Failure Modes: (a) non-insulated walls, (b) insulated walls.

Figure 2.2. Average Temperatures Measured during Wall Test W4.

Figure 2.3. Average Temperatures Measured during Wall Test W5.

Figure 2.4. Average Temperatures Measured during Wall Test W6.

Figure 2.5. Average Deflections Measured during Wall Test W4.

Figure 2.6. Average Deflections Measured during Wall Test W5.

Figure 2.7. Average Deflections Measured during Wall Test W6.

Figure 2.8. Average Temperatures Measured at Central and End Studs (Test W4).

Figure 2.9. Average Temperatures Measured at Central and End Studs (Test W5).

Figure 2.10. Average Temperatures Measured at Central and End Studs (Test W6).

Chapter 3

Numerical Simulations of Wall Tests

The analytical part of this research project included numerical simulations of tests W1-W6 described in Section 1.3 and Chapter 2. These simulations are described in this chapter.

3.1. Heat Transfer Simulations

Retrospective numerical simulations of temperature histories in tests W1-W6 were conducted using the computer program TRACE (Temperature Rise Across Construction Elements). This program was developed, within the scope of this research project, based on an explicit finite-difference integration algorithm (Sultan 1996) to solve one-dimensional transient heat transfer equations. The user manual for the program, including a numerical example and the FORTRAN source code, is presented in Appendix B.

The apparent thermal properties of wall materials used in the heat transfer simulations are summarized in Tables 3.1 and 3.2. These properties are also illustrated in Figures 3.1-3.4. The presence of the steel frame was neglected in the heat transfer simulations, because, due to the light weight of thin gauge members, they play a minor role in the heat transfer

mechanism. Temperature histories were generated at the boundaries shown in Figure 1.11 designated by Roman figures. The simulated histories, designated by respective boundary figures, are presented in Figures 3.5-3.10 (curves with symbols) along with respective measured temperatures.

A large number of numerical trial runs have been conducted to arrive at a single set of thermal properties that would produce a reasonable agreement of simulated and measured temperature histories at all four simulated boundaries in all six tests. In other words, the properties listed in Tables 3.1 and 3.2 were essentially calibrated to produce a good match of numerical and test results. The calibration process was to start numerical simulations with a set of thermal properties, reported in the literature, and compare the output histories with measured temperatures. Then after changing a thermal property in a narrow temperature interval, one at a time, a trial numerical run would be conducted and the output results checked for a better agreement with experimental data. This procedure was repeated many times first to calibrate the properties of gypsum board to match measured temperature histories of test W6 (non-insulated wall test of the longest duration with all gypsum board staying in place until the end of the test). Secondly, these gypsum board properties were verified in the simulation of test W4 (non-insulated wall test of shorter duration with observed fall-off of the face layer of gypsum board). The third step was to apply the calibrated gypsum board properties in the simulations of tests W1-W3 and W5 (insulated walls) and calibrate the properties of insulation materials (rock fibre batts, glass fibre batts and loose fill cellulose).

The apparent material properties, thermal conductivity and heat capacity at temperatures up to 1000°C, were found to have a great deal of influence on the shape of simulated time-temperature curves. It should be mentioned, however, that these apparent thermal properties, to some degree, implicitly account for physical phenomena other than heat transfer, such as mass transfer, phase change, etc. This happens because the temperature rise in LSF walls exposed to fire is affected by processes not described by heat transfer, such as migration of moisture vapors, penetration of cool ambient air or hot furnace gases into the cavity, etc.

Another parameter that has a major effect on simulated temperature histories is the fall-off time of gypsum board layers. TRACE models the spalling of gypsum board by removing it from the simulation at a user-specified time. The fall-off times listed in Tables 1.1 and 2.1 reflect the beginning of layer spalling based on visual test observations. In the retrospective simulations, these times were slightly adjusted (increased) for tests W2-W5 in order to represent a time when a significant portion of the layer had fallen off. In both simulated and measured temperature histories, the fall-off of gypsum board layers is usually manifested in respective time-temperature curves by sudden shifts in temperature closely approaching the furnace temperature.

Sensitivity analysis was conducted for all other numerical parameters, and it should be mentioned that simulated temperature histories are not very sensitive to the choice of emissivity coefficients and even less sensitive to the choice of convection coefficients. In the simulations shown in Figures 3.5-3.10, the emissivity of the furnace fire and the emissivity of the fire exposed gypsum board surface was 0.9, giving a combined

emissivity coefficient of 0.81. The emissivity of gypsum board surfaces in the wall cavity was 0.8, giving a combined emissivity coefficient of 0.667. The emissivity coefficient for the gypsum board surface on the unexposed side was 0.7.

3.2. Structural Model

The structural behaviour of an LSF wall, exposed to fire on one side, is modelled here by a single stud with initial imperfection subjected to eccentric tributary load, P , as shown in Figure 3.11. The following assumptions are employed:

- Steel stress-strain relationships at elevated temperatures are linear up to the yield strength.
- Flexural-torsional and weak axis buckling failure modes are prevented by adequate lateral restraints (bridging and blocking).
- The stud is hinged at the ends, as the load eccentricity in part models rotational end restraints.
- There is no temperature variation in the vertical direction along the stud; however, the temperature varies across the stud section from T_H at the hot flange to T_C at the cold flange.

The above assumptions are essentially those suggested by Klippstein (1978), except for the assumption of eccentric loading, which re-examines the earlier assumption of concentric load application. Further, assuming a linear gradient of thermal elongation strain across the stud section, the thermal bowing curvature, ϕ , can be expressed by

$$\phi = \alpha_T \delta_T / D \quad (3.1)$$

where the thermal expansion coefficient α_T for steel (Lie 1992) is

$$\alpha_T = (12 + 0.004 T_A) \cdot 10^{-6} \quad (3.2)$$

and

D = stud section depth,

$\delta_T = T_H - T_C$ = temperature difference across stud section in °C,

$T_A = 0.5 (T_H + T_C)$ = average stud temperature in °C.

Then, the shape of the stress-free initial imperfection, $y_1(z)$, caused by thermal bowing, is

$$y_1(z) = 0.5 \phi z (H - z) \quad (3.3)$$

The vertical load, P , acting with an eccentricity, e , causes secondary lateral deflection, $y_2(z)$, as shown in Figure 3.11. The differential equation for the system

$$-EI^* y_2''(z) = P [y_1(z) + y_2(z) - e] \quad (3.4)$$

can be solved for the total lateral deflection

$$y(z) = y_1(z) + y_2(z) = (\phi \beta^{-2} - e) [\tan(0.5\beta H) \sin(\beta z) + \cos(\beta z) - 1] \quad (3.5)$$

$$\text{where} \quad \beta^2 = P / (EI^*) \quad (3.6)$$

I^* = elasticity-modulus-weighted moment of inertia of the unreduced stud section about the neutral axis parallel to flanges, and

$E = 203000$ MPa = steel modulus of elasticity at room temperature.

The simulations shown in this chapter use the reduction coefficient, n_T , based on Equation 1.6, for the steel modulus of elasticity at elevated temperatures

$$n_T = E_T / E = 1.0 - 3.0 \cdot 10^{-4} T + 3.7 \cdot 10^{-7} T^2 - 6.1 \cdot 10^{-9} T^3 + 5.4 \cdot 10^{-12} T^4 \quad (3.7)$$

Due to the temperature variation from the hot flange to the cold flange, the modulus of elasticity varies across the steel stud section, and the 'modulus-weighted' moment of

inertia in Equation 3.6 accounts for this variation. I^* can be quantified numerically by dividing the stud section into a sufficiently large number, q , of two-dimensional elements, so that

$$I^* = \sum_{i=1}^q n_i [I_i + A_i (x_i - c)^2] \quad (3.8)$$

where

n_i = reduction factor for temperature T_i , calculated using Equation 3.7,

I_i = moment of inertia of element i about its own neutral axis parallel to flanges,

A_i = area of element i ,

x_i = distance of element i from the extreme fibre of the cold flange,

T_i = temperature of element i , calculated from

$$T_i = T_C + (\delta_T x_i / D) \quad (3.9)$$

and

c = distance from the centroidal axis of the 'modulus-weighted' section to the extreme fibre of the cold flange, calculated from

$$c = \frac{\sum_{i=1}^q n_i A_i x_i}{\sum_{i=1}^q n_i A_i} \quad (3.10)$$

The eccentricity, e , appears in the model for the following reasons (see Figure 3.12):

- As the temperature gradient develops across the stud, and the modulus of elasticity deteriorates at the hot flange, the centre of the steel section shifts towards the cold flange.

- The test loading conditions for LSF walls were close to loading between two parallel plates. Therefore, rotation of stud ends, associated with stress-free thermal bowing, causes the shift of the load towards the hot flange.
- The assumed stress-free thermal bowing is an idealization of the real stress condition caused by non-uniform heating. Eccentricity in part simulates internal stresses caused by non-linear thermal strain gradients.

The above three factors that contribute to the development of the model eccentricity strongly depends on δ_T , and it is convenient to assume e proportional to $\phi \beta^{-2}$

$$e = (1 - K_R) \phi \beta^{-2} \quad (3.11)$$

where K_R is a reduction coefficient.

Substitution of Equation 3.11 into Equation 3.5 for $z=0.5H$ gives the expression for the lateral deflection, Δ , at the mid-height of the stud

$$\Delta = K_R \phi \beta^{-2} [1 / \cos(0.5\beta H) - 1] \quad (3.12)$$

Equations 3.1-3.12 were incorporated into the computer program STUD that has been developed to model the structural behaviour of loadbearing LSF walls in fire resistance tests. The user manual for the program, including numerical example and FORTRAN source code, is presented in Appendix C. It should also be mentioned, that the algorithm of the program conservatively assumes the calculated deflections to remain constant whenever δ_T decreases in time (as occurs in the final stages of fire tests on non-insulated walls). In STUD simulations, the values of Δ and $y(z)$ at any given time step are not allowed to be less than in the previous step. This measure was first suggested by Gerlich (1995) in order to account for the creep and stress relaxation phenomena in steel studs at

temperatures higher than 400°C, and it was especially useful in lateral deflection simulations for tests W4 and W6.

Simulated mid-height lateral deflection histories for tests W1-W6 are presented in Figures 3.13-3.18 (lines with symbols) along with respective measured deflections. For these simulations, average temperatures measured at locations 2a and 4a in the central part of specimens, were used for T_H and T_C input, respectively. For all test simulations, the value of $K_R = 0.6$ proved to produce a reasonably good agreement of simulated and measured deflections until the initiation of structural failure mechanisms in central studs. Examination of Equations 3.1-3.12 suggests that for K_R values less than $0.5(0.5\beta H)^2 [1 / \cos(0.5\beta H) - 1]$ the model eccentricity, e , is large enough to cause negative secondary deflections, $y_2(z)$, and that is essentially what happens in the simulated tests. In other words, the numerical simulations suggest that the development of stress-free thermal bowing is restrained (reduced), primarily, by the rotational restraints at stud ends and by the non-linearity of thermal strain gradients across stud sections. At δ_T values in excess of 350°C, these effects cause critical compressive stresses in the hot flanges at stud ends, which is evident from the structural failure mode observed in tests on insulated walls.

The major advantage of the proposed structural model is that it permits the simulation of both dominant failure modes, observed in tests, depending on the heating regime of the studs. As long as lateral deflections are properly simulated, the structural failure of studs can be predicted using conventional formulas from S136-94, for members subjected to combined compression and bending, adjusted to account for the deterioration of the mechanical properties of steel at elevated temperatures.

For insulated walls, a critical section near stud ends should be checked for the compressive failure of the hot flange. In STUD structural failure simulations for walls W1-W3 and W5, the perforated section at $z = 0.2 H$ was checked, using the following failure criterion:

$$f_H = n_H \left(\frac{P}{A_e^*} + \frac{P[e - y(0.2H)]}{S_{eH}^*} \right) \geq F_{yH} \quad (3.13)$$

where

f_H = compressive stress at the extreme fibre of the hot flange,

n_H = reduction factor for temperature T_H , calculated using Equation 3.7,

F_{yH} = yield strength of steel at temperature T_H , calculated using Equation 1.5,

A_e^* = elasticity-modulus-weighted effective stud section area in compression, and

S_{eH}^* = elasticity-modulus-weighted effective stud section modulus in bending that causes compression of hot flange.

The width of compression elements in effective stud cross-sections was reduced in accordance with Clause 5.6.2 of S136-94 to account for local buckling effects. For perforated sections, the web was considered to consist of two unstiffened elements, one on each side of perforation, according to Clause 6.8.1 of S136-94. Effective cross-section dimensions were assumed to be insensitive to temperature, thus, they were based on steel properties at room temperature and compressive stress $f = F_y$. These effective cross-sections were used in the calculation of the temperature dependent ‘modulus-weighted’ properties A_e^* and S_{eH}^* (using an approach similar to evaluation of I^* in Equation 3.8)

$$A_e^* = \sum_{i=1}^q n_i A_i \quad (3.14)$$

$$S_{eH}^* = \sum_{i=1}^q n_i [I_i + A_i (x_i - c)^2] / (D - c) \quad (3.15)$$

For non-insulated LSF walls, the section at (or near) stud mid-height should be checked for the compressive failure of the cold flange. In STUD structural failure simulations for walls W4 and W6, the perforated section at $z = 0.4 H$ was checked, using the following failure criterion:

$$f_C = n_C \left(\frac{P}{A_e^*} + \frac{P y(0.4H)}{S_{eC}^*} \right) \geq F_{yC} \quad (3.16)$$

where

f_C = compressive stress at the extreme fibre of the cold flange,

n_C = reduction factor for temperature T_C , calculated using Equation 3.7,

F_{yC} = yield strength of steel at temperature T_C , calculated using Equation 1.5, and

S_{eC}^* = elasticity-modulus-weighted effective stud section modulus in bending that causes compression of cold flange, calculated from

$$S_{eC}^* = \sum_{i=1}^q n_i [I_i + A_i (x_i - c)^2] / c \quad (3.17)$$

It should be emphasized that sectional properties A_e^* , S_{eH}^* and S_{eC}^* are based on three different effective cross-sections, because the configurations of compression elements are different in each case. Also note, that eccentricity, e , does not appear in Equation 3.16.

As δ_T decreases in the final stages of tests on non-insulated walls, the heating rate in cold flange becomes higher than in hot flange. This effect, combined with creep and stress relaxation phenomena in steel at temperatures higher than 400°C, causes gradual

reduction of eccentricity. Therefore, the use of $e = 0$ in the expression for structural failure criterion is appropriate for non-insulated walls.

The STUD program conducts structural failure checks of Equations 3.13 and 3.16 at every time step in the simulation, thus, it can generate predictions of the structural failure time. Table 3.3 lists such predictions for Tests W1-W6 based on measured temperature histories, and also, based on TRACE-simulated temperatures. Predictions for non-insulated walls W4 and W6 show a reasonable agreement with test structural failure times. For insulated walls W1-W3 and W5, predicted failure times agree well with the initiation of structural failure in central studs. The latter is consistent with the quasi-elastic approach used in the STUD model formulation and the effect of load redistribution to colder studs at wall ends in the final phases of the tests. As expected, predictions based on measured temperatures generally show a better agreement with test results than predictions based on simulated temperatures.

Table 3.1. Apparent Thermal Properties of Firecode C Core Type X Gypsum Board (12.7 mm thick, bulk density 750 kg/m³).

Apparent thermal properties	Temperature range (°C)											
	<50	50-80	80-100	100-120	120-140	140-160	160-180	180-200	200-300	300-500	500-700	>700
Conductivity [W/(m°C)]	0.27	0.27	0.27	0.15	0.15	0.15	0.15	0.15	0.17	0.17	0.25	0.45
Heat capacity [MJ/(m ³ °C)]	0.49	0.70	1.4	2.8	5.6	9.1	7.0	2.8	2.8	1.4	0.49	0.35

Table 3.2. Apparent Thermal Properties of Insulation Materials.

Insulation type (bulk density in kg/m ³)	Apparent heat capacity [MJ/(m ³ °C)]	Apparent thermal conductivity [W/(m°C)] in temperature range (°C)						
		<80	80-200	200-300	300-400	400-500	500-700	>700
Rock fibre batts (33 kg/m ³)	0.027	1.0	0.50	0.10	0.10	1.5	2.0	3.0
Glass fibre batts (10 kg/m ³)	0.009	1.0	0.50	0.10	0.10	1.5	2.0	3.0
Loose fill cellulose (47 kg/m ³)	0.115	1.0	0.3	0.30	0.30	1.0	1.0	2.0

Table 3.3. Comparison of Predicted Failure Times with Test Results.

Assembly number	Insulation type (fibre)	Structural failure time in test (min.)	Initiation of failure in central studs in test (min.)	STUD predictions based on measured temperatures (min.)	STUD predictions based on simulated temperatures (min.)
W1	Glass	55	49	50	51
W2	Rock	73	50	52	52
W3	Cellulose	70	60	59	54
W4	-	76	N/A	77	73
W5	Rock	59	48	48	52
W6	-	83	N/A	84	85

Figure 3.1. Apparent Thermal Conductivity of Gypsum Board.

Figure 3.2. Apparent Heat Capacity of Gypsum Board.

Figure 3.3. Apparent Thermal Conductivity of Rock and Glass Fibre Insulation.

Figure 3.4. Apparent Thermal Conductivity of Dry Blown Cellulose.

Figure 3.5. Comparison of Simulated and Measured Temperatures (Test W1).

Figure 3.6. Comparison of Simulated and Measured Temperatures (Test W2).

Figure 3.7. Comparison of Simulated and Measured Temperatures (Test W3).

Figure 3.8. Comparison of Simulated and Measured Temperatures (Test W4).

Figure 3.9. Comparison of Simulated and Measured Temperatures (Test W5).

Figure 3.10. Comparison of Simulated and Measured Temperatures (Test W6).

Figure 3.11. Thermal Bowing and Secondary Deflection.

Figure 3.12. Stud End Conditions: (a) uniform heating, (b) non-uniform heating.

Figure 3.13. Comparison of Simulated and Measured Mid-Height Deflections (Test W1).

Figure 3.14. Comparison of Simulated and Measured Mid-Height Deflections (Test W2).

Figure 3.15. Comparison of Simulated and Measured Mid-Height Deflections (Test W3).

Figure 3.16. Comparison of Simulated and Measured Mid-Height Deflections (Test W4).

Figure 3.17. Comparison of Simulated and Measured Mid-Height Deflections (Test W5).

Figure 3.18. Comparison of Simulated and Measured Mid-Height Deflections (Test W6).

Chapter 4

LSF Floor Tests and Numerical Simulations

The analytical part of this research project included retrospective simulations of five standard fire resistance tests on unrestrained LSF floor tests (Sultan et al 1998). A brief description of these tests, followed by a detailed description of the numerical simulations, is presented in this chapter.

4.1. Fire Resistance Tests

The floor assemblies tested (designated FF-22 through FF-25 and FF-27) were 4800 mm long by 3892 mm wide. Floor framing consisted of galvanized cold formed steel joists spanning the shorter dimension (effective span 3805 mm). The lateral stability of joists was ensured by channel tracks and web stiffeners at joist ends, blocking at 2-3 locations, flat strap bridging (bottom flange plane) at joist mid-span, and the plywood sub-floor (upper flange plane). All connections were performed using screws – no welding was used. Steel frame fabrication details reflected the common practices used in North America. All steel joists had a C-shaped cross-section, nominally, 203 mm deep by 41.3 mm wide, with 12.7-mm flange stiffening lips and base metal thickness of 1.21 mm

(Manufacturers' Standard Gauge 18). The minimum specified steel yield strength was $F_y = 230$ MPa. In each floor assembly, ten resilient channels, spaced 406 mm o.c., were attached perpendicular to joists to support the gypsum board ceilings. Additional resilient channels were installed in assembly FF-25 (with one layer of gypsum board) to support gypsum board ends. The resilient channels, 14 mm deep by 58 mm wide, were fabricated from 0.6-mm thick galvanized steel sheets. The channels had a 34-mm wide web, designed to support the gypsum board connections, and one 18-mm wide flattened flange lip connected to the bottom flanges of steel joists by 19-mm long self-drilling screws. The cross-sectional details of the floor specimens are illustrated in Figure 4.1. Complete description of floor construction and test procedures is presented elsewhere (Sultan et al 1998).

The gypsum board (nominal thickness 12.7 mm) used in all tests had the "Firecode C Core Type X" designation and met the requirements for Type X gypsum board. It was supplied in 3048×1219-mm sheets. Gypsum board from two different shipments (from the same manufacturer) was used in this test series, and there was a notable difference in the density per unit area of gypsum board used in test FF-27 (9.55 kg/m^2) and that used in tests FF-22 through FF-25 (10.2 kg/m^2). The gypsum board sheets were attached perpendicular to resilient channels by screws 25-41 mm long, spaced 300 mm o.c. along resilient channels.

Table 4.1 lists the parameters of the tests. Two types of insulation were used in this test series: glass fibre batts (10 kg/m^3) and rock fibre batts (33 kg/m^3), both 90 mm thick. The concrete used for the sub-floor in test FF-27 had a density of 2406 kg/m^3 and a

compressive strength of 25 MPa (after 28 days). The applied loads in all tests reflect the maximum (100%) load condition, according to CAN/ULC-S101-M89, and steel joist bending strength limit state, according to S136-94.

In addition to standard instrumentation, numerous thermocouples were placed within each floor assembly in order to obtain temperature histories at various locations during fire tests. The generalized locations of these thermocouples are shown in Figure 4.1 designated by Arabic figures. Figures 4.8-4.12 show histories of average measured temperatures designated by respective generalized location numbers. Vertical deflections were measured at mid-span and quarter-span locations of three joists in the central part of each floor. The average measured mid-span deflection histories are shown in Figures 4.16-4.20.

A short summary of test results is provided in Table 4.1. The listed structural failure times represent the number of completed elapsed minutes for which the floor specimens maintained their ability to sustain the applied load. The structural failure in all tests was manifested through the significant drop in the hydraulic pressure of the loading system and large “run-away” deflections. It was usually accompanied by the penetration of flames and hot gases (integrity failure) through the joints between sub-floor plywood sheets that were opening due to large floor deflections. Figure 4.2 illustrates a LSF floor assembly after a fire test. Close inspection of steel joists after fire tests indicated that the dominant structural failure mode was the compressive failure (local buckling) of joist top flange near mid-span, as shown in Figure 4.3. Heat insulation failure was not detected in any of the tests. The maximum temperature rise, measured by thermocouples under

standard pads on the unexposed side of floor specimens, reached only 93.1°C (in Test FF-22).

Gypsum board fall-off times, shown in the Table 4.1, indicate the number of completed elapsed minutes before the fall-off of a layer piece not less than 500 mm in any dimension. These times reflect the beginning of gypsum board layer fall-off. It usually took several minutes for a gypsum board layer to fall-off completely. In all cases, the fall-off occurred due to the deterioration of the mechanical properties of the gypsum board around attachment screws (usually, starting at a corner, or near an end, or an edge of a gypsum board sheet). Close inspection of floor assemblies after fire tests indicated that resilient channels remained properly attached to joists, and board attachment screws remained attached to resilient channels.

Although the author of this thesis did not witness the tests, he interviewed several test witnesses and reviewed numerous observation reports, video tapes, slides, photographs and other documents pertaining to the tests. The following trends in the behaviour of unrestrained LSF floors, exposed to standard fire, have been established based on experimental observations and measured data:

- Comparison of Tests FF-23 and FF-24 suggests that joist spacing has no effect on the fire resistance of LSF floors. Contrary to generally held belief, wider joist spacing in LSF floors should not be associated with a reduction in their fire resistance (provided that the protective ceiling is not attached directly to the joists).
- One layer of 12.7-mm thick fire resistant gypsum board provides about 15 minutes delay, and 2 layers of 12.7-mm thick fire resistant gypsum board provide about 40

minutes delay, in the temperature rise in the bottom flanges of steel joists (generalized location 2).

- Insulation restricts the passage (and dissipation) of heat through the floor cavity causing an accelerated temperature rise in the bottom flanges (and in the gypsum board ceiling), and a delayed temperature rise in the top flanges of the joists. Therefore, the heating regime in insulated floors features high temperature gradients across the steel joist section, while the heating regime of joists in non-insulated floors is rather close to uniform heating. The development of higher temperature gradients in insulated floors cause larger deflections, due to the associated thermal bowing of joists, compared to non-insulated floors.
- Temperature data from Test FF-25 suggests that steel joists can maintain their loadbearing capacity even when bottom flange temperatures exceed 800°C. The temperature rise in the top flange appears to be more critical.
- The fire resistance of LSF floors is governed by the ability of the gypsum board ceiling to remain in place. This is especially evident in non-insulated floor Test FF-22, where the structural failure occurred immediately after the base gypsum layer began to fall-off and joist top flanges became directly exposed to furnace fire. Glass fibre insulation in tests FF-23 and FF-24 was not able to delay the critical heating of joist top flanges by more than 3-4 minutes, after the fall-off of the gypsum board, because the glass fiber insulation melts when directly exposed to fire. In contrast to that, rock fibre insulation (which does not melt) in Test FF-25 delayed the critical

heating of joist top flanges (thus, delaying the structural failure) by 11 minutes after the fall-off of the gypsum board ceiling.

- Comparison of gypsum board fall-off times in Tests FF-22 through FF-24 suggests that accelerated temperature rise in the ceilings of insulated LSF floors reduces the ability of gypsum board to remain in place by 7-10 minutes. As a result, it may be concluded, that glass fibre insulation placed in floor cavity reduces the fire resistance of LSF floors by about 5 minutes. This trend, however, does not apply to rock fibre insulation because of the delaying effect described in the previous paragraph.

4.2. Heat Transfer Simulations

One-dimensional heat transfer numerical simulations were conducted for all tests using the computer program TRACE. As in earlier wall test simulations, the presence of the steel frame was neglected in the modelling of transient heat transfer across LSF floors. Figure 4.1 shows the locations of simulation boundaries, designated by Roman figures. Simulated temperature histories, at these boundaries, are shown in Figures 4.8-4.12 (curves with symbols) along with measured temperatures.

The apparent thermal properties of gypsum board and insulation materials that earlier produced good results for wall tests (listed in Tables 3.1 and 3.2) were also used for floor test simulations. The higher density per unit area of gypsum board sheets in Tests FF-22 through FF-25 was modelled by proportionately increasing the thickness of gypsum board layers from the nominal value of 12.7 mm to 13.5 mm. It is worthwhile to note

again, that the choice of thermal properties for gypsum board and insulation materials has a major influence on the shape of simulated temperature curves.

The apparent thermal properties of plywood and concrete at elevated temperatures, used in the simulations, are listed in Tables 4.2 and 4.3. These properties are also illustrated in Figures 4.4-4.7. It should be mentioned, however, that the choice of thermal properties for plywood and concrete was of little significance, because these materials were located away from the fire exposed side. Values listed in Tables 4.2 and 4.3 are based on properties suggested by Lie (1992).

In LSF floor tests (as in the wall tests), the fall-off of gypsum board layers is manifested in respective time-temperature curves by sudden shifts in temperature (closely approaching furnace temperature). As mentioned earlier, TRACE models gypsum board fall-off (and melting of glass fibre insulation) by removing the respective layer from the simulation at a user-specified time, and this input parameter is of importance for the accuracy of the simulations. The fall-off times listed in Table 4.1 reflect the beginning of gypsum board layer fall-off based on visual test observations. In the numerical simulations, these times were slightly adjusted (increased by 1-2 minutes) in order to represent a time when a significant portion of the layer had fallen off.

As can be observed in Figures 4.8, 4.10 and 4.11, the agreement of simulated and measured temperatures for boundaries II and IV was not as good as in the wall tests. Numerous attempts to achieve a better match by the adjustment of thermal properties of gypsum board and insulation materials were not successful. This led the author of this thesis to suggest that there was a cooling phenomenon present in the floor cavity which

was not described by heat transfer equations. One possible reason for this cavity cooling effect is that the negative furnace pressure causes the ambient air to enter the floor cavity through the unsealed plywood sub-floor joints, mix with the hot smoke in the cavity, and continue its way into the furnace through the gypsum board joints. The good agreement of simulated and measured temperatures achieved in test FF-27, where the concrete topping sealed the floor assembly and minimized ambient air penetration, adds to the credibility of this suggestion. Visual observation of flames coming out from the gypsum board joints during floor tests (indicating the flow of hot gases from the cavity into the furnace) also support this explanation of the cooling effect.

An attempt was made to simulate the cavity cooling effect by assuming the cavity to consume heat. This was done simply by introducing a coefficient of Cavity Heat Loss (CHL) for a cavity layer in the TRACE program. In earlier simulations, at every time step, the net heat leaving the hotter surface of the cavity was completely absorbed by the cooler side surface (algorithm equivalent to $CHL=1.0$). In the new simulations, at every time step, the net heat absorbed by the cooler surface of the cavity would be equal to the net heat emitted by the hotter side multiplied by CHL. This computational procedure led to improved simulations of tests FF-22 (with $CHL=0.7$) and FF-25 (with $CHL=0.5$), as shown in Figures 4.13 and 4.14, respectively.

4.3. Structural Simulations

The special purpose computer program JOIST was developed to simulate deflection histories of unrestrained LSF floors exposed to fire and generate predictions of structural

failure times. The user manual for the program, including a numerical example and FORTRAN source code, is presented in Appendix D. The computational model of the program is based on the following assumptions:

- LSF floor is modelled by a single unrestrained simply supported joist subjected to a vertical tributary line load, ω , due to the applied load and floor self-weight.
- Lateral and torsional failure modes are prevented by adequate lateral restraints.
- Sub-floors do not contribute to bending resistance of LSF floors.
- There is no temperature variation in the horizontal direction along the joist; however, the temperature varies across the joist section from T_H at the hot (bottom) flange to T_C at the cold (top) flange.
- Steel stress-strain relationships at elevated temperatures are linear up to the yield strength.

For the simulations presented in this chapter, steel properties at elevated temperatures based on Equations 1.5, 1.6 and 1.11 were used. At any time step during fire test simulation, the total deflection $y(x)$ of the steel joist, at any distance x from the left support, was computed as

$$y(x) = y_B(x) + y_D(x) \quad (4.1)$$

where

$$y_B(x) = 0.5 x (L - x) (\varepsilon_T(T_H) - \varepsilon_T(T_C)) / D \quad (4.2)$$

$$y_D(x) = y_S(x) - y_0(x) \quad (4.3)$$

$$y_S(x) = \iint \phi_S(x) dx dx \quad (4.4)$$

$$y_0(x) = \omega x (L^3 - 2Lx^2 + x^3) / (24EI) \quad (4.5)$$

$y_B(x)$ = deflection due to stress-free thermal bowing (based on the assumption of linear thermal strain gradient across the joist section),

$y_D(x)$ = deflection due to deterioration of stiffness of the heated joist section,

$y_S(x)$ = deflection of heated joist due to tributary load ω ,

$y_0(x)$ = initial deflection of unheated joist due to tributary load ω ,

$L = 3805$ mm = joist span,

$\varepsilon_T(T_H)$ = thermal strain of joist hot flange at temperature T_H , calculated using Equation 1.11,

$\varepsilon_T(T_C)$ = thermal strain of joist cold flange at temperature T_C , calculated using Equation 1.11,

$D = 203.2$ mm = depth of the joist section,

$\phi_S(x)$ = curvature of heated joist section due to bending moment $M(x) = 0.5 \omega x (L - x)$, caused by tributary load ω , and

I = moment of inertia of unreduced joist section about a neutral axis perpendicular to the web.

The $M(x)$ and $\phi_S(x)$ diagrams are schematically illustrated in Figure 4.15. JOIST program computes $y_S(x)$ values by dividing the joist span into 200 segments, calculating average curvature values $\phi_S(x)$ for each segment, and performing the double integration of Equation 4.4 numerically. The curvature values $\phi_S(x)$, for corresponding moments $M(x)$, are found from moment-curvature relationships that are generated at each time step (i.e. for every T_H and T_C temperature input pair). The program computes the non-linear

moment-curvature relationships using the standard iterative procedures of sectional analysis based on the assumption of linear variation of mechanical (stress-related) strains across the joist section (i.e. the common ‘plain sections remain plain’ assumption) and the equilibrium of tensile and compressive forces. For these iterations, the effective joist section is divided into 100 two-dimensional elements with assigned temperatures (and associated mechanical properties of Equations 1.5 and 1.6) based on the distance of the element from the hot flange (linear temperature gradient assumed). The width of top flanges (under compressive stress) is reduced in effective cross-sections in accordance with Clause 5.6.2. of S136-94 to account for local buckling effects. It is assumed that effective cross-section dimensions are insensitive to temperature, thus, they are computed based on steel properties at room temperature and compressive stress $f = F_y$.

The simulated mid-span deflection histories are presented in Figures 4.16-4.20 (lines with symbols) compared with respective measured deflections. For these simulations, the average temperatures measured at generalized locations 2a and 4a were used for T_H and T_C input. Calculated deflections are in reasonable agreement with measured deflections in all tests except for test FF-25 (Figure 4.19), where simulated deflections significantly overestimate measured deflections in the final phase of the test. It could be presumed, that the presence of rock fibre insulation in Test FF-25 delays temperature rise in joist webs causing significant non-linearity in temperature (and thermal strain) gradients across joist section. Such non-linearity leads to reduced thermal bowing and associated state of internal stress that has an unloading effect, as explained in Appendix D. An

improved mid-span deflection simulation for test FF-25, achieved by using a reduction coefficient of $R = 0.8$ for $y_B(x)$ values, is shown in Figure 4.21.

In general, inspection of detailed numerical output (and hand calculation checks) indicated that thermal bowing deflections $y_B(x)$ in all tests constitute more than 85% of the total deflection $y(x)$ at any time except for the last few minutes before structural failure. Deflection component $y_D(x)$, associated with the deterioration of joist stiffness due to heating, does not contribute much to floor deflections until the initiation of the failure mechanism (i.e. until the reduced bending capacity of heated joist approaches the level of the bending moment acting at joist mid-span). A sample comparison of $y_B(x)$ and $y_D(x)$ values (see numerical columns for DRth and Dst, respectively) is provided in Section D.4.2.

The JOIST program was designed to generate predictions of structural failure times by conducting failure checks at every time step of the simulation using the following criterion:

$$M_R < M(0.5L) \quad (4.6)$$

where

$M(0.5L) = 0.125 \omega L^2$ = bending moment at joist mid-span due to tributary load ω , and M_R = inelastic bending capacity of effective cross-section of heated joist, where tensile strains (in the hot flange) are not limited, but compressive strains (in the cold flange) are limited to yield strain. This formulation of M_R is consistent with Clause 6.4.2. of S136-94, and the program performs the necessary calculations using iterative sectional analysis procedures described above.

Table 4.4 lists JOIST predictions of structural failure times, for considered LSF floor tests, based on measured and TRACE-simulated temperatures. As expected, predictions based on measured temperatures show somewhat better agreement with test results than predictions based on simulated temperatures. All predictions are slightly below test results, and that is consistent with somewhat conservative failure criterion and assumptions used in the model.

Table 4.1. Summary of Fire Resistance Tests on Unrestrained LSF Floors.

Specimen number	Joist spacing (mm)	Gypsum board ceiling thickness (mm)	Insulation type (mm)	Sub-floor thickness (mm)	Applied load (kN/m ²)	Fall-off time of gypsum board on exposed side (min)		Structural failure time (min)
						Face layer	Base layer	
FF-22	406	2 × 12.7	-	Plywood (15.9)	2.9	66	73	73
FF-23	406	2 × 12.7	Glass	Plywood (15.9)	2.9	59	63	67
FF-24	610	2 × 12.7	Glass	Plywood (19.0)	1.8	59	65	68
FF-25	406	1 × 12.7	Rock	Plywood (15.9)	2.9	35	N/A	46
FF-27	406	2 × 12.7	Glass	Plywood (15.9)+Concrete (51.0)	1.9	49	53	61

Table 4.2. Apparent Thermal Properties of Softwood Plywood (bulk density 500 kg/m³).

Apparent thermal properties	Temperature range (°C)						
	<100	100-200	200-250	250-300	300-350	350-500	>500
Conductivity [W/(m°C)]	0.15	0.2	0.2	0.1	0.1	0.1	0.15
Heat capacity [MJ/(m ³ °C)]	0.75	2.4	1.3	1.3	0.4	0.55	0.55

Table 4.3. Apparent Thermal Properties of Concrete (bulk density 2400 kg/m³).

Apparent thermal properties	Temperature range (°C)						
	<100	100-200	200-400	400-500	500-600	600-800	>800
Conductivity [W/(m°C)]	1.8	1.8	1.55	1.55	1.4	1.4	1.1
Heat capacity [MJ/(m ³ °C)]	1.9	2.5	2.5	3.5	3.5	2.5	2.5

Table 4.4. Comparison of Predicted Failure Times with Test Results.

Assembly number	Structural failure time in test (min.)	JOIST predictions based on measured temperatures (min.)	JOIST predictions based on simulated temperatures (min.)
FF-22	73	73	71
FF-23	67	65	63
FF-24	68	66	63
FF-25	46	45	43
FF-27	61	56	55

Figure 4.1. Locations of Temperature Measurements and Simulation Boundaries.

Figure 4.2. General View of a LSF Floor Assembly after Fire Test.

Figure 4.3. Compressive Failure (Local Buckling) of Top Flanges near Mid-Span.

Figure 4.4. Apparent Heat Capacity of Softwood Plywood.

Figure 4.5. Apparent Thermal Conductivity of Softwood Plywood.

Figure 4.6. Apparent Thermal Capacity of Concrete.

Figure 4.7. Apparent Thermal Conductivity of Concrete.

Figure 4.8. Comparison of Simulated and Measured Temperatures (Test FF-22).

Figure 4.9. Comparison of Simulated and Measured Temperatures (Test FF-23).

Figure 4.10. Comparison of Simulated and Measured Temperatures (Test FF-24).

Figure 4.11. Comparison of Simulated and Measured Temperatures (Test FF-25).

Figure 4.12. Comparison of Simulated and Measured Temperatures (Test FF-27).

Figure 4.13. Improved Simulation of Test FF-22 with Cavity CHL=0.7.

Figure 4.14. Improved Simulation of Test FF-25 with Cavity CHL=0.5.

Figure 4.15. Moment and Curvature Diagrams for an Unrestrained Joist.

Figure 4.16. Comparison of Simulated and Measured Mid-Span Deflections (Test FF-22).

Figure 4.17. Comparison of Simulated and Measured Mid-Span Deflections (Test FF-23).

Figure 4.18. Comparison of Simulated and Measured Mid-Span Deflections (Test FF-24).

Figure 4.19. Comparison of Simulated and Measured Mid-Span Deflections (Test FF-25).

Figure 4.20. Comparison of Simulated and Measured Mid-Span Deflections (Test FF-27).

Figure 4.21. Improved Simulation of Test FF-25 with $R=0.8$.

Chapter 5

Summary and Conclusions

5.1 Summary

A combined analytical and experimental investigation was conducted to study the behaviour of LSF wall and floor assemblies in standard fire resistance tests. An extensive literature review was conducted on the fire resistance of loadbearing LSF walls and the properties of associated materials at elevated temperatures. Three wall assemblies were tested under load and standard fire exposure to investigate the effects of cavity insulation, resilient channels and stud spacing on fire resistance. Comprehensive fire resistance models for LSF wall and floors were developed and codified in three computer programs. Retrospective numerical thermal and structural simulations were conducted for six loadbearing wall tests and five floor tests. Apparent thermal properties were calibrated for fire resistant gypsum board and three types of cavity insulation materials. Structural failure criteria were developed for heated studs and joists based on the failure modes observed in tests. Analytical predictions of fire resistance were compared with experimental results.

5.2 Conclusions

The following conclusions can be drawn from the research reported in this thesis:

- Insulation placed in the cavity of loadbearing LSF walls reduces their fire resistance because it reduces the ability of fire exposed gypsum board to remain in place and because it causes non-uniform heating of the loadbearing steel studs.
- Wider stud spacing in loadbearing LSF walls does not necessarily reduce their fire resistance in standard tests, especially, when fire exposed gypsum board is attached to resilient channels.
- Resilient channels on the fire exposed side of loadbearing LSF walls reduce their fire resistance in standard tests, because they reduce the ability of gypsum board to remain in place.
- Loading reduces the fire resistance of LSF walls.
- The structural behaviour of steel studs in fire resistance tests is sensitive to non-uniform heating and rotational end restraints, as is evident from the observed failure modes and verified by numerical simulations.
- Conventional design of lateral restraints in LSF assemblies, to prevent flexural-torsional and weak axis buckling failure modes of steel studs and joists at normal temperatures, appears to be adequate for fire conditions.
- The ability of gypsum board to remain in place is of major significance for the fire resistance of LSF assemblies, as is evident from test observations and verified by numerical simulations.

- The TRACE program can be used with a high degree of confidence to generate temperature histories in multi-layered construction assemblies heated on one side, provided the heating event can be classified as one-dimensional heat transfer and the apparent thermal properties of the materials are known. On the other hand, if the temperature histories at several interfaces are known from experiment, TRACE can be used to calibrate the apparent thermal properties.
- Comparative TRACE simulations point to the possibility of a cavity cooling effect in floor tests, caused by the flow of ambient air through the cavity into the furnace, due to negative furnace pressure.
- As demonstrated in STUD and JOIST simulations, the conventional principles of structural design for cold formed steel structures adjusted for the deterioration of the mechanical properties of steel at elevated temperatures, can be applied to the design of LSF members under fire exposure. However, STUD simulations also demonstrate that thermally-induced deformations can cause significant changes in the configuration of heated structures leading to unusual stress re-distributions and unexpected (counter-intuitive) failure modes.
- STUD and JOIST simulations indicate that thermal bowing (not deterioration of steel stiffness) is responsible for the major part of deflections observed in fire resistance tests on LSF walls and floors.

5.3 Recommendations for Future Research

- Further research is recommended on the mechanical properties of cold formed steel at elevated temperatures, including the development of rigorous high temperature creep and stress relaxation models.
- A much broader experimental database on the fire resistance of LSF assemblies is needed. Among the experimental parameters to be further investigated are non-standard fire exposures, various types of gypsum board, effects of stud/joist shape, thickness, depth and slenderness, rotational end restraint conditions and realistic loading arrangements in loadbearing wall tests.
- The fall-off time of the gypsum board is identified as a parameter that significantly affects the fire resistance of LSF assemblies. More experimental data should be collected before reliable predictions of this parameter can be made. Further research is also recommended on the thermal properties of various gypsum board products at elevated temperatures.
- As more experimental data becomes available, further development, validation and refinement of analytical/numerical fire resistance models will be needed.

Appendix A

Detailed Fire Resistance Test Data

The experimental data measured during fire resistance tests W4-W6 are presented in this Appendix. Individual thermocouple and deformation gauge records are grouped by respective location to facilitate comparison and evaluation of data scatter. Temperature and deformation histories for test W4 are shown in Figures A.1 through A.14. Plots in Figures A.15 through A.28 pertain to test W5. Detailed data for test W6 are shown in Figures A.29-A.42. In plots pertaining to lateral deflections, the positive direction indicates movement towards the furnace. In Figures A.14, A.28 and A.42, the positive direction indicates the upward displacement of the loading beam.

Figure A.1. Test W4: Temperatures Measured at Locations 1 and 1a: Upper Level.

Figure A.2. Test W4: Temperatures Measured at Locations 1 and 1a: Lower Level.

Figure A.3. Test W4: Temperatures Measured at Locations 2 and 2a: Upper Level.

Figure A.4. Test W4: Temperatures Measured at Locations 2 and 2a: Lower Level.

Figure A.5. Test W4: Temperatures Measured at Location 3: Upper Level.

Figure A.6. Test W4: Temperatures Measured at Location 3: Lower Level.

Figure A.7. Test W4: Temperatures Measured at Locations 4 and 4a: Upper Level.

Figure A.8. Test W4: Temperatures Measured at Locations 4 and 4a: Lower Level.

Figure A.9. Test W4: Temperatures Measured at Locations 5 and 5a: Upper Level.

Figure A.10. Test W4: Temperatures Measured at Locations 5 and 5a: Lower Level.

Figure A.11. Test W4: Measured Lateral Deflections: Upper Level.

Figure A.12. Test W4: Measured Lateral Deflections: Mid-Height Level.

Figure A.13. Test W4: Measured Lateral Deflections: Lower Level.

Figure A.14. Test W4: Measured Vertical Displacements of Loading Beam.

Figure A.15. Test W5: Temperatures Measured at Locations 1 and 1a: Upper Level.

Figure A.16. Test W5: Temperatures Measured at Locations 1 and 1a: Lower Level.

Figure A.17. Test W5: Temperatures Measured at Locations 2 and 2a: Upper Level.

Figure A.18. Test W5: Temperatures Measured at Locations 2 and 2a: Lower Level.

Figure A.19. Test W5: Temperatures Measured at Location 3: Upper Level.

Figure A.20. Test W5: Temperatures Measured at Location 3: Lower Level.

Figure A.21. Test W5: Temperatures Measured at Locations 4 and 4a: Upper Level.

Figure A.22. Test W5: Temperatures Measured at Locations 4 and 4a: Lower Level.

Figure A.23. Test W5: Temperatures Measured at Locations 5 and 5a: Upper Level.

Figure A.24. Test W5: Temperatures Measured at Locations 5 and 5a: Lower Level.

Figure A.25. Test W5: Measured Lateral Deflections: Upper Level.

Figure A.26. Test W5: Measured Lateral Deflections: Mid-Height Level.

Figure A.27. Test W5: Measured Lateral Deflections: Lower Level.

Figure A.28. Test W5: Measured Vertical Displacements of Loading Beam.

Figure A.29. Test W6: Temperatures Measured at Locations 1 and 1a: Upper Level.

Figure A.30. Test W6: Temperatures Measured at Locations 1 and 1a: Lower Level.

Figure A.31. Test W6: Temperatures Measured at Locations 2 and 2a: Upper Level.

Figure A.32. Test W6: Temperatures Measured at Locations 2 and 2a: Lower Level.

Figure A.33. Test W6: Temperatures Measured at Location 3: Upper Level.

Figure A.34. Test W6: Temperatures Measured at Location 3: Lower Level.

Figure A.35. Test W6: Temperatures Measured at Locations 4 and 4a: Upper Level.

Figure A.36. Test W6: Temperatures Measured at Locations 4 and 4a: Lower Level.

Figure A.37. Test W6: Temperatures Measured at Locations 5 and 5a: Upper Level.

Figure A.38. Test W6: Temperatures Measured at Locations 5 and 5a: Lower Level.

Figure A.39. Test W6: Measured Lateral Deflections: Upper Level.

Figure A.40. Test W6: Measured Lateral Deflections: Mid-Height Level.

Figure A.41. Test W6: Measured Lateral Deflections: Lower Level.

Figure A.42. Test W6: Measured Vertical Displacements of Loading Beam.

Appendix B

Computer Program TRACE

User Manual

B.1. Introduction

For any building structure, the accidental situation of fully developed fire exposure can be analyzed as an ultimate limit state event that is likely to cause significant damage. A detailed understanding of the nature of this event is required for the proper design of fire resistant construction assemblies and structural systems in buildings. The TRACE (Temperature Rise Across Construction Assemblies) program was developed for the purpose of investigating temperature rise and heat flux patterns in multi-layered construction assemblies subjected to fire on one side. The theoretical background information for this type of problem is given elsewhere (Harmathy 1961).

Computational techniques are becoming increasingly important as research and design tools in structural fire protection. Numerical models are especially needed where a non-standard fire exposure must be considered. The TRACE program can be used for numerical simulations of standard fire resistance tests (e.g. ASTM E119, ISO 834) or for object-oriented design based on parametric (non-standard) time-temperature curves.

TRACE simulates one-dimensional radiation, convection and conduction heat transfer. It is not intended for simulation of events where significant mass transfer occurs. However, TRACE generates accurate predictions of temperature and heat flux histories (at specified locations of interest) within construction assemblies subjected to transient heat transfer events with limited mass transfer. The accuracy of these predictions largely depends on the choice of high-temperature material thermal properties used in the numerical simulations. On the other hand, when temperature histories are obtained experimentally, the program can be used to calibrate the 'apparent' thermal properties of construction materials at high temperatures.

TRACE is a research tool that can be used to optimize experimental programs in fire resistance. Numerical results provide additional information that helps in the analysis of test data. TRACE simulations can also be used for parametric studies.

It should be noted that the applicability of TRACE for fire safety design purposes is limited by the lack of reliable information on the thermal properties of construction materials. At elevated temperatures, many building materials undergo physico-chemical changes, and their thermal properties change substantially within the temperature range associated with building fires. These properties are also sensitive to other parameters such as heating rate, temperature gradient, etc. In addition, the movement (mass transfer) of hot moisture and gases considerably affects the development of temperatures across construction assemblies subjected to fire. These phenomena should be kept in mind when using TRACE program for fire resistance modelling.

B.2. Program Description

The source code for the TRACE program is presented in Section B.5. The implemented explicit integration algorithm for one-dimensional transient heat transfer closely follows procedures described by Sultan (1996). The explanatory notes in the source code provide brief descriptions of the computational routines and the parameters used in the program.

The TRACE program was successfully compiled and tested using Digital Visual Fortran Version 5.0. The executable file occupies 385 KB of storage space. The program code is compliant with standard Fortran 77, and therefore, older versions of Fortran compilers can also be used.

An input file, in ASCII text format, has to be generated and saved before program execution. At the start, the program prompts the user for the names of the input file and the output file. These names should be entered on the keyboard during program execution. The program will create an output file with the specified name and write down the output data to that file. The output file is an ASCII text file, which can be easily imported into a spreadsheet application for post-processing.

The flowchart of the TRACE program is shown in Figure B.1. The main program opens the input and output files, performs the integration of the finite difference equations, checks for numerical stability, and writes the results to the output file. In addition to the main program, TRACE contains seven subroutines: DATAIN, NODES, FIRE, GYPSUM, INSLTN, WOOD and CONCRT. Subroutine DATAIN reads the input file, checks the input data and echoes it to the output file. Subroutine NODES performs the discretization of the construction assembly, generates nodes and computes their distance from the fire-exposed surface, assigns node identification numbers, specifies boundary nodes. The FIRE subroutine computes the current fire temperatures at the fire-exposed

surface of the assembly. The remaining four subroutines are material subroutines that compute the temperature-dependant thermal properties for all nodes at each time step.

The time increment, TS, should be chosen sufficiently small to ensure the numerical stability of the explicit integration algorithm (Sultan 1996). The program checks the stability criteria for all nodes at every time step during the simulation. During execution, the program will display the lowest stability criterion (and the associated node and time) for each output step OTS. This information is also written to the output file. Whenever the chosen time increment exceeds a stability criterion at any node, the program will display an error message and stop the execution. In such cases, the simulation should be repeated with reduced TS.

The current version of the program provides for the simulation of ASTM E119 and ISO 834 fires only. However, any desired time-temperature regime can be specified with a little addition to the source code of subroutine FIRE.

TRACE program allows for the modelling of spalling (fall-off) or melting of some construction materials at high temperatures, observed in many fire scenarios. The user can specify the fall-off time for any material layer that will be directly exposed to fire during the simulation. The program will remove that layer at the specified time and continue the simulation without that layer. After fall-off, the output temperatures at all the nodes in the removed material layer will be equal to the fire temperature, and the heat flux at these nodes will show 0 values in the output.

Subroutines GYPSUM, INSLTN, WOOD and CONCRT specify temperature-dependent thermal properties for several types of gypsum board, insulation, wood products and concrete, respectively, using special functions contained in the program. These functions reflect thermal properties obtained from literature or calibrated from test results. New subroutines and functions can be easily added to the program to extend its applicability to other types of materials or in order to conduct parametric studies on thermal properties.

At every output time step, OTS, the program writes to the output file the time, the temperature of fire, the temperatures of all boundary nodes, the minimum stability criterion with the associated node and time, and records to memory the heat flux values at all boundary nodes. At every profile output time step, PRTS, the program records to memory the temperatures of all nodes (temperature profiles). After the completion all calculations and printing out the temperature histories at boundary nodes, the program writes to the output file the heat flux histories and the temperature profiles that are accumulated in memory during program execution.

It should be noted that TRACE is a unit-sensitive program. All input parameters must be in SI units: seconds (s), degrees Celsius (°C) and meters (m). These units are also implied in the output file for time, temperature and distance values, respectively. The heat flow values in the output file are in Watts per square meter (W/m^2).

B.3. Input File Format

The order of input data by sequence of parameters needed by TRACE is as follows:

1. Title line for problem identification (one line of up to 80 alphanumeric characters, including spaces).
2. Basic parameters line consisting of seven parameters separated by commas:
TMAX, TS, OTS, IOFT, EMIF, AC, NOL, PRTS.
3. Material layer lines (one line for each material layer; air cavities count as material layers) in sequence starting with the line for the fire-exposed material layer and ending with line for the material layer on the ambient side. Each line consists of six parameters separated by commas:
ITOM, ISOM, DML, NODX, EMI, TFAL.

Integer values should be entered for parameters, starting with letters I-N. Real values should be entered for all other parameters.

TMAX= total time (in seconds) of fire-exposure/heat transfer simulation.

TS = time increment step (in seconds).
TS should be smaller than numerical stability criteria, SCR, at any node at any time during the simulation.

OTS = output time step (in seconds), for writing boundary node temperatures to the output file (e.g. enter 60. for 1-minute intervals).
Current dimension of the program limits the number of OTS steps to 1999 (i.e. the condition $TMAX / OTS < 2000$ must be observed).
The program will also write to the output file the minimum SCR with the associated node and time for each OTS period.
The program will also write to the output file the heat flux for every boundary node at every OTS step.

IOFT = indicator of fire type
1 for ASTM E119 time-temperature curve (approximated formula).
2 for ISO 834 time-temperature curve.

EMIF = emissivity of fire.

AC = ambient temperature (in °C).

NOL = number of material layers in the wall assembly (cavities count as material layers). Current dimension of the program limits NOL to 10.

PRTS = temperature profile output time step (in seconds), for writing all node temperatures to the output file (e.g. enter 300. for 5-min. time intervals). Enter a value larger than TMAX if no temperature profiles desired in output. Current dimension of the program limits the number of PRTS steps to 20 (i.e. the condition $TMAX / PRTS < 21$ must be observed).

ITOM = indicator for type of material.
 1 for gypsum board (currently has subtypes 1-6).
 2 for insulation (currently has subtypes 1-7).
 3 for cavity (no subtypes).
 4 for wood products (currently has subtype 1).
 5 for concrete (currently has subtype 1).

ISOM = indicator for subtype of material.
 1 for Type X gypsum board, with properties according to Sultan (1996). The following four subtypes of materials were calibrated from test data, according to Alfawakhiri et al (2000):
 6 calibrated for Type C gypsum board, 12.7 mm thick.
 4 calibrated for insulation made of cellulose fibres treated with fire retardants (dry blown, loose fill, bulk density 47 kg/cu.m).
 5 calibrated for rock fibre insulation (bulk density 33 kg/cu.m).
 7 calibrated for glass fibre insulation (bulk density 10 kg/cu.m).
 Subtypes 2-5 for gypsum board, subtypes 1-3 & 6 for insulation, subtype 1 for wood products and subtype 1 for concrete are currently used for parametric studies. Routines and functions associated with these subtypes can be modified to investigate various thermal properties.

DML = thickness of material layer (in meters).

NODX = number of discretization layers (finite elements) for the material layer. Enter any integer value for cavity layers (the program will not generate finite elements within cavity layers). Current dimension of the program limits the total number of finite elements to 999 (i.e. the sum of NODX values for all material layers in the input file should be less than 1000).

EMI = emissivity of the material layer surface.
 For cavity layers, the program assigns the 'emissivity' through the cavity layer based on the combined emissivity of solid material layers before and after the cavity layer (Sultan, 1996). The program will read the EMI value entered for any cavity layer and assign it to the CHL (Coefficient of Heat Loss) value of the

cavity. In most cases, the value of unity should be entered for $EMI=CHL$ of cavity layers, which corresponds to complete transfer of the net heat, by means of convection and radiation, from the hotter surface of cavity to the colder surface (i.e. $EMI=CHL=1.0$ means that cavity does not consume or generate any heat). Values of $CHL>1.0$ can be entered to simulate penetration of hot gases from the furnace into the cavity (with associated accelerated heating effect). Values of $CHL<1.0$ can be used to simulate penetration of ambient air into the cavity (with associated cooling effect). At every time step, the net heat entering the colder surface of the cavity will be equal to the net heat leaving the hotter surface of the cavity multiplied by user-specified $EMI=CHL$.

TFAL = time of fall-off (in seconds), spalling or melting, for material layer.

The program removes the material layer from the assembly when the time of fall-off is reached in the simulation.

Enter a value larger than **TMAX**, if no fall-off is desired.

The fall-off of material layers can proceed only in sequence starting from the fire-exposed side (i.e., the fall-off time of a material layer cannot be less than the fall-off time of any material layer that is closer to the fire-exposed side).

B.4. Numerical Example

The use of TRACE is illustrated here by an 85-minute simulation of heat transfer through lightweight steel framed (LSF) wall, shown in Figure B.2. The wall is subjected to standard ASTM E119 fire on one side. It is lined with two layers of 12.7 mm thick, Type C, gypsum board on each side. The thermal properties of the gypsum board are shown in Table B.1. (these thermal properties are codified within TRACE as material subtype 6 of material type 1). The fire-exposed gypsum board is assumed to stay in place for the duration of the simulation. The steel studs (and the wall cavity) are 92 mm deep. The contribution of the steel studs to heat transfer is neglected. The locations of boundaries are shown in Figure B.2, designated by Roman figures.

The input and output files are listed in the following subsections. The integration is conducted with a time step of 0.1 seconds. The output time step, for temperature and heat flux histories, is 1 minute. Ten-minute intervals are specified for temperature profile output. The simulated temperature histories, heat flux histories and temperature profiles are plotted in Figures B.3, B.4 and B.5, respectively.

B.4.1. Input File

```
LSF WALL SFF3 (TRACE RUN)
5100.,0.1,60.,1,0.9,20.,5,600.
1,6,0.0127,20,0.9,5101.
1,6,0.0127,20,0.8,5101.
3,0,0.092,1,1.,5101.
1,6,0.0127,20,0.8,5101.
1,6,0.0127,20,0.7,5101.
```

B.4.2. Output File

1

```
LSF WALL SFF3 (TRACE RUN)

DURATION OF THE SIMULATION      =      5100.
TIME INCREMENT STEP             =      0.10000
OUTPUT TIME STEP                 =      60.
TIME-TEMPERATURE CURVE TYPE     =      1
EMISSIVITY OF FIRE              =      0.900
AMBIENT TEMPERATURE             =      20.00
NUMBER OF MATERIAL LAYERS       =      5
TEMP. PROFILE OUTPUT TIME STEP  =      600.

LAYER NUMBER                     =      1
TYPE OF MATERIAL                 =      1
SUBTYPE OF MATERIAL             =      6
THICKNESS                       =      0.0127
NUMBER OF (dx) ELEMENTS        =      20
EMISSIVITY                      =      0.900
FALL-OFF TIME                   =      5101.

LAYER NUMBER                     =      2
TYPE OF MATERIAL                 =      1
SUBTYPE OF MATERIAL             =      6
THICKNESS                       =      0.0127
NUMBER OF (dx) ELEMENTS        =      20
EMISSIVITY                      =      0.800
FALL-OFF TIME                   =      5101.

LAYER NUMBER                     =      3
TYPE OF MATERIAL                 =      3
SUBTYPE OF MATERIAL             =      0
THICKNESS                       =      0.0920
NUMBER OF (dx) ELEMENTS        =      1
EMISSIVITY                      =      0.667
FALL-OFF TIME                   =      5101.

LAYER NUMBER                     =      4
TYPE OF MATERIAL                 =      1
SUBTYPE OF MATERIAL             =      6
THICKNESS                       =      0.0127
NUMBER OF (dx) ELEMENTS        =      20
EMISSIVITY                      =      0.800
FALL-OFF TIME                   =      5101.

LAYER NUMBER                     =      5
TYPE OF MATERIAL                 =      1
SUBTYPE OF MATERIAL             =      6
THICKNESS                       =      0.0127
NUMBER OF (dx) ELEMENTS        =      20
EMISSIVITY                      =      0.700
FALL-OFF TIME                   =      5101.
```

TOTAL NUMBER OF NODES = 82
 TOTAL NUMBER OF BOUNDARIES = 6

TIME	FIRE	BOUNDARY NODES						MIN. STABILITY	AT	AT
sec.	deg.C	1	21	41	42	62	82	CRITERION	NODE	TIME
0.	20.0	20.0	20.0	20.0	20.0	20.0	20.0			
60.	332.5	111.4	23.5	20.0	20.0	20.0	20.0	0.35110	1	19.600
120.	426.0	176.3	36.7	21.9	20.1	20.0	20.0	0.36097	41	120.000
180.	487.1	247.7	48.2	27.4	20.8	20.0	20.0	0.36001	41	180.000
240.	532.5	317.6	57.3	34.2	22.2	20.2	20.0	0.35932	41	240.000
300.	568.5	385.3	65.1	40.9	24.0	20.6	20.1	0.35881	41	300.000
360.	598.0	442.9	71.9	46.6	26.0	21.2	20.3	0.35844	41	360.000
420.	623.1	489.7	77.8	51.0	28.0	22.0	20.6	0.35820	42	420.000
480.	644.7	525.4	82.8	55.4	30.1	23.0	21.1	0.34423	1	480.000
540.	663.6	554.9	87.3	59.6	32.2	24.1	21.7	0.29643	1	540.000
600.	680.3	580.8	91.7	63.5	34.4	25.3	22.5	0.29135	1	600.000
660.	695.3	604.1	95.4	67.0	36.5	26.6	23.3	0.28668	1	660.000
720.	708.8	627.2	99.4	70.2	38.7	27.9	24.2	0.28226	1	720.000
780.	721.2	644.7	104.7	72.9	40.7	29.4	25.2	0.27858	1	780.000
840.	732.4	660.3	111.1	75.4	42.7	30.8	26.2	0.27525	1	840.000
900.	742.8	676.7	118.0	77.5	44.6	32.3	27.3	0.27194	1	900.000
960.	752.4	689.5	125.3	79.4	46.5	33.8	28.4	0.26914	1	960.000
1020.	761.2	699.0	133.9	81.3	48.2	35.3	29.5	0.14998	1	1019.600
1080.	769.5	712.3	143.9	83.3	50.0	36.8	30.6	0.14886	1	1080.000
1140.	777.3	719.0	156.8	85.2	51.7	38.2	31.8	0.12237	1	1140.000
1200.	784.6	730.9	173.3	87.2	53.3	39.6	32.9	0.12164	1	1200.000
1260.	791.4	738.9	192.7	89.0	54.9	41.0	33.9	0.12107	1	1260.000
1320.	797.9	747.9	211.0	90.8	56.4	42.4	35.0	0.12046	1	1320.000
1380.	804.0	754.7	228.5	92.5	57.9	43.7	36.0	0.11996	1	1380.000
1440.	809.8	761.7	247.7	94.0	59.4	45.0	37.0	0.11945	1	1438.400
1500.	815.3	769.2	266.9	95.5	60.8	46.2	38.0	0.11895	1	1500.000
1560.	820.5	774.7	286.1	96.9	62.2	47.4	38.9	0.11852	1	1560.000
1620.	825.5	782.2	306.4	97.9	63.5	48.5	39.8	0.11803	1	1620.000
1680.	830.3	787.0	325.8	99.1	64.7	49.6	40.7	0.11764	1	1680.000
1740.	834.9	793.9	345.0	100.7	66.0	50.6	41.5	0.11719	1	1740.000
1800.	839.3	798.4	364.5	103.0	67.4	51.6	42.3	0.11683	1	1800.000
1860.	843.5	804.4	383.3	105.7	69.0	52.6	43.1	0.11643	1	1860.000
1920.	847.5	809.2	401.4	108.6	70.8	53.7	43.8	0.11607	1	1920.000
1980.	851.4	813.9	420.6	111.6	72.6	54.8	44.5	0.11572	1	1980.000
2040.	855.2	819.1	436.7	114.6	74.5	55.9	45.3	0.11536	1	2040.000
2100.	858.8	822.9	456.1	117.6	76.5	57.1	46.0	0.11506	1	2100.000
2160.	862.4	827.8	472.6	120.4	78.5	58.3	46.8	0.11473	1	2160.000
2220.	865.7	831.2	489.9	123.8	80.5	59.5	47.5	0.11445	1	2220.000
2280.	869.0	835.8	502.6	127.9	82.7	60.8	48.3	0.11413	1	2280.000
2340.	872.2	838.9	516.3	132.5	84.9	62.2	49.1	0.11387	1	2340.000
2400.	875.3	843.1	525.3	137.2	87.4	63.5	49.9	0.11358	1	2400.000
2460.	878.3	846.8	537.2	142.0	89.9	64.9	50.8	0.11331	1	2460.000
2520.	881.2	850.1	546.7	148.5	92.8	66.4	51.7	0.11305	1	2520.000
2580.	884.1	853.8	557.8	157.2	96.4	67.9	52.6	0.11279	1	2580.000
2640.	886.9	856.7	567.4	169.8	101.5	69.5	53.6	0.11255	1	2640.000
2700.	889.6	860.3	578.1	190.3	109.5	71.2	54.7	0.11230	1	2700.000
2760.	892.2	863.1	587.6	208.1	119.1	73.0	55.8	0.11208	1	2760.000
2820.	894.8	866.5	597.6	222.5	126.9	74.9	56.9	0.11183	1	2820.000
2880.	897.3	869.4	609.1	236.2	134.4	76.7	58.1	0.11161	1	2880.000
2940.	899.7	872.5	619.2	249.8	141.7	78.5	59.4	0.11138	1	2940.000
3000.	902.1	875.4	631.5	263.5	149.1	80.1	60.6	0.11117	1	3000.000
3060.	904.4	878.5	642.2	277.7	156.6	81.7	61.8	0.11095	1	3060.000
3120.	906.7	881.2	654.2	292.5	165.2	83.3	63.0	0.11074	1	3120.000
3180.	909.0	884.2	663.2	306.6	173.9	84.8	64.1	0.11052	1	3180.000
3240.	911.2	886.8	675.4	319.0	184.6	86.2	65.2	0.11033	1	3240.000
3300.	913.3	889.7	686.1	330.5	194.5	87.5	66.2	0.11012	1	3300.000
3360.	915.5	892.1	694.9	341.6	205.6	88.8	67.1	0.10993	1	3360.000
3420.	917.5	894.8	700.7	352.2	216.4	90.0	68.0	0.10974	1	3420.000
3480.	919.6	897.1	707.3	361.9	227.1	91.2	68.8	0.10956	1	3480.000
3540.	921.6	899.6	709.8	371.7	238.0	92.4	69.6	0.10937	1	3540.000
3600.	923.6	901.7	714.9	380.5	248.8	93.6	70.4	0.10920	1	3600.000
3660.	925.5	904.1	719.5	389.4	259.6	94.6	71.1	0.10903	1	3660.000

3720.	927.4	906.1	721.4	396.8	269.9	95.6	71.8	0.10887	1	3720.000
3780.	929.3	908.3	725.1	405.6	280.5	96.7	72.5	0.10870	1	3780.000
3840.	931.1	910.4	728.9	412.2	290.4	97.9	73.2	0.10853	1	3840.000
3900.	932.9	912.3	730.1	420.2	300.2	98.8	73.9	0.10838	1	3900.000
3960.	934.7	914.3	733.3	427.3	310.7	100.1	74.5	0.10822	1	3960.000
4020.	936.5	916.3	736.9	433.1	319.8	101.6	75.1	0.10807	1	4020.000
4080.	938.2	918.1	737.6	441.4	330.4	103.7	75.8	0.10792	1	4080.000
4140.	939.9	919.9	740.4	448.0	340.1	105.4	76.4	0.10777	1	4140.000
4200.	941.6	921.9	743.6	453.8	349.6	107.6	77.0	0.10762	1	4200.000
4260.	943.3	923.7	745.1	462.0	359.2	109.6	77.6	0.10748	1	4260.000
4320.	944.9	925.4	746.9	468.6	369.1	111.7	78.2	0.10734	1	4320.000
4380.	946.6	927.2	749.9	474.2	377.8	113.9	78.8	0.10720	1	4380.000
4440.	948.2	929.0	753.1	483.0	387.2	116.1	79.4	0.10706	1	4440.000
4500.	949.8	930.7	753.6	488.5	396.7	118.3	80.0	0.10692	1	4500.000
4560.	951.3	932.3	756.0	494.3	405.1	120.6	80.6	0.10679	1	4560.000
4620.	952.9	934.0	759.0	499.6	413.1	123.0	81.2	0.10665	1	4620.000
4680.	954.4	935.8	761.9	506.2	421.6	125.5	81.8	0.10652	1	4680.000
4740.	955.9	937.3	762.5	512.0	429.5	128.3	82.4	0.10639	1	4740.000
4800.	957.4	938.9	765.3	517.3	437.1	131.1	83.1	0.10626	1	4800.000
4860.	958.9	940.6	768.3	522.2	444.1	134.1	83.7	0.10613	1	4860.000
4920.	960.3	942.2	769.6	527.7	451.2	137.2	84.3	0.10600	1	4920.000
4980.	961.8	943.7	772.1	533.1	458.4	140.5	85.0	0.10588	1	4980.000
5040.	963.2	945.4	775.0	537.9	465.2	143.8	85.6	0.10575	1	5040.000
5100.	964.6	947.0	776.9	542.8	471.6	147.7	86.2	0.10563	1	5100.000

TIME	HEAT FLUX (W/sq.m.) AT BOUNDARY NODES					
sec.	1	21	41	42	62	82
0.	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
60.	0.6416E+04	0.3303E+03	0.9539E+00	0.1754E+00	0.1525E-03	0.5769E-08
120.	0.1056E+05	0.8187E+03	0.2055E+02	0.1043E+02	0.2151E+00	0.4049E-03
180.	0.1335E+05	0.9277E+03	0.6259E+02	0.4566E+02	0.3174E+01	0.2451E-01
240.	0.1495E+05	0.9961E+03	0.1118E+03	0.9390E+02	0.1243E+02	0.2144E+00
300.	0.1538E+05	0.1010E+04	0.1582E+03	0.1419E+03	0.2780E+02	0.8304E+00
360.	0.1516E+05	0.9989E+03	0.1955E+03	0.1823E+03	0.4673E+02	0.2118E+01
420.	0.1471E+05	0.9723E+03	0.2261E+03	0.2103E+03	0.6621E+02	0.4222E+01
480.	0.1446E+05	0.1025E+04	0.2545E+03	0.2385E+03	0.8408E+02	0.7160E+01
540.	0.1425E+05	0.1035E+04	0.2804E+03	0.2654E+03	0.1010E+03	0.1087E+02
600.	0.1397E+05	0.1092E+04	0.3029E+03	0.2891E+03	0.1173E+03	0.1531E+02
660.	0.1358E+05	0.1063E+04	0.3215E+03	0.3091E+03	0.1326E+03	0.2044E+02
720.	0.1286E+05	0.1144E+04	0.3362E+03	0.3252E+03	0.1468E+03	0.2619E+02
780.	0.1260E+05	0.1226E+04	0.3471E+03	0.3375E+03	0.1596E+03	0.3249E+02
840.	0.1237E+05	0.1431E+04	0.3552E+03	0.3465E+03	0.1710E+03	0.3925E+02
900.	0.1178E+05	0.1627E+04	0.3598E+03	0.3527E+03	0.1809E+03	0.4637E+02
960.	0.1158E+05	0.2069E+04	0.3632E+03	0.3567E+03	0.1894E+03	0.5376E+02
1020.	0.1213E+05	0.2545E+04	0.3757E+03	0.3611E+03	0.1968E+03	0.6133E+02
1080.	0.1118E+05	0.3455E+04	0.3820E+03	0.3672E+03	0.2036E+03	0.6900E+02
1140.	0.1164E+05	0.4503E+04	0.3886E+03	0.3743E+03	0.2102E+03	0.7673E+02
1200.	0.1100E+05	0.5448E+04	0.3956E+03	0.3815E+03	0.2158E+03	0.8450E+02
1260.	0.1100E+05	0.5778E+04	0.4026E+03	0.3883E+03	0.2207E+03	0.9223E+02
1320.	0.1068E+05	0.6174E+04	0.4064E+03	0.3944E+03	0.2252E+03	0.9988E+02
1380.	0.1072E+05	0.6599E+04	0.4099E+03	0.3989E+03	0.2291E+03	0.1074E+03
1440.	0.1065E+05	0.6879E+04	0.4147E+03	0.4028E+03	0.2327E+03	0.1148E+03
1500.	0.1040E+05	0.7198E+04	0.4200E+03	0.4066E+03	0.2358E+03	0.1221E+03
1560.	0.1049E+05	0.7519E+04	0.4099E+03	0.4094E+03	0.2386E+03	0.1291E+03
1620.	0.1008E+05	0.7640E+04	0.4160E+03	0.4085E+03	0.2410E+03	0.1360E+03
1680.	0.1022E+05	0.7804E+04	0.4222E+03	0.4098E+03	0.2431E+03	0.1426E+03
1740.	0.9814E+04	0.7785E+04	0.4485E+03	0.4167E+03	0.2490E+03	0.1490E+03
1800.	0.9902E+04	0.7891E+04	0.4714E+03	0.4335E+03	0.2555E+03	0.1552E+03
1860.	0.9619E+04	0.8108E+04	0.4945E+03	0.4530E+03	0.2640E+03	0.1612E+03
1920.	0.9526E+04	0.7977E+04	0.5184E+03	0.4743E+03	0.2739E+03	0.1671E+03
1980.	0.9437E+04	0.8182E+04	0.5423E+03	0.4965E+03	0.2853E+03	0.1730E+03
2040.	0.9184E+04	0.8040E+04	0.5659E+03	0.5189E+03	0.2980E+03	0.1790E+03
2100.	0.9244E+04	0.8230E+04	0.5809E+03	0.5403E+03	0.3113E+03	0.1851E+03
2160.	0.8979E+04	0.7295E+04	0.6401E+03	0.5584E+03	0.3251E+03	0.1914E+03
2220.	0.9074E+04	0.8258E+04	0.6988E+03	0.5865E+03	0.3391E+03	0.1980E+03
2280.	0.8817E+04	0.8323E+04	0.7558E+03	0.6259E+03	0.3532E+03	0.2046E+03
2340.	0.8897E+04	0.8146E+04	0.8144E+03	0.6736E+03	0.3671E+03	0.2113E+03

2400.	0.8680E+04	0.8152E+04	0.8542E+03	0.7238E+03	0.3813E+03	0.2185E+03
2460.	0.8579E+04	0.7961E+04	0.1039E+04	0.7740E+03	0.3960E+03	0.2269E+03
2520.	0.8545E+04	0.8021E+04	0.1216E+04	0.8523E+03	0.4105E+03	0.2350E+03
2580.	0.8374E+04	0.7799E+04	0.1481E+04	0.9692E+03	0.4267E+03	0.2435E+03
2640.	0.8404E+04	0.7900E+04	0.1672E+04	0.1150E+04	0.4462E+03	0.2523E+03
2700.	0.8228E+04	0.7682E+04	0.1773E+04	0.1484E+04	0.4685E+03	0.2618E+03
2760.	0.8239E+04	0.7761E+04	0.1985E+04	0.1758E+04	0.4894E+03	0.2719E+03
2820.	0.8065E+04	0.7657E+04	0.2209E+04	0.2001E+04	0.5083E+03	0.2826E+03
2880.	0.7986E+04	0.7572E+04	0.2452E+04	0.2251E+04	0.5202E+03	0.2939E+03
2940.	0.7865E+04	0.7380E+04	0.2715E+04	0.2518E+04	0.5305E+03	0.3053E+03
3000.	0.7763E+04	0.7412E+04	0.3013E+04	0.2806E+04	0.5435E+03	0.3168E+03
3060.	0.7614E+04	0.7107E+04	0.3356E+04	0.3134E+04	0.5592E+03	0.3281E+03
3120.	0.7532E+04	0.7111E+04	0.3705E+04	0.3484E+04	0.5714E+03	0.3390E+03
3180.	0.7354E+04	0.6922E+04	0.3923E+04	0.3826E+04	0.5810E+03	0.3495E+03
3240.	0.7277E+04	0.6901E+04	0.4162E+04	0.4071E+04	0.5890E+03	0.3595E+03
3300.	0.7104E+04	0.7941E+04	0.4392E+04	0.4311E+04	0.5980E+03	0.3690E+03
3360.	0.7053E+04	0.6690E+04	0.4594E+04	0.4515E+04	0.6131E+03	0.3781E+03
3420.	0.6912E+04	0.6838E+04	0.4786E+04	0.4709E+04	0.6156E+03	0.3867E+03
3480.	0.6869E+04	0.6555E+04	0.4943E+04	0.4867E+04	0.6160E+03	0.3949E+03
3540.	0.6756E+04	0.6852E+04	0.5097E+04	0.5033E+04	0.6154E+03	0.4027E+03
3600.	0.6738E+04	0.6482E+04	0.5227E+04	0.5150E+04	0.6475E+03	0.4103E+03
3660.	0.6654E+04	0.6400E+04	0.5328E+04	0.5270E+04	0.6474E+03	0.4176E+03
3720.	0.6643E+04	0.6427E+04	0.5407E+04	0.5332E+04	0.6415E+03	0.4248E+03
3780.	0.6589E+04	0.6373E+04	0.5507E+04	0.5453E+04	0.6208E+03	0.4318E+03
3840.	0.6524E+04	0.6342E+04	0.5526E+04	0.5479E+04	0.6836E+03	0.4385E+03
3900.	0.6537E+04	0.6367E+04	0.5646E+04	0.5582E+04	0.6747E+03	0.4452E+03
3960.	0.6503E+04	0.6308E+04	0.5647E+04	0.5601E+04	0.6559E+03	0.4520E+03
4020.	0.6450E+04	0.6249E+04	0.5639E+04	0.5597E+04	0.7431E+03	0.4584E+03
4080.	0.6459E+04	0.6329E+04	0.5739E+04	0.5679E+04	0.7559E+03	0.4649E+03
4140.	0.6446E+04	0.6270E+04	0.5730E+04	0.5686E+04	0.8078E+03	0.4715E+03
4200.	0.6403E+04	0.6216E+04	0.5688E+04	0.5646E+04	0.8311E+03	0.4777E+03
4260.	0.6360E+04	0.6355E+04	0.5813E+04	0.5756E+04	0.8554E+03	0.4845E+03
4320.	0.6395E+04	0.6243E+04	0.5779E+04	0.5734E+04	0.9059E+03	0.4905E+03
4380.	0.6363E+04	0.6187E+04	0.5741E+04	0.5702E+04	0.9272E+03	0.4972E+03
4440.	0.6317E+04	0.6139E+04	0.5919E+04	0.5862E+04	0.9665E+03	0.5032E+03
4500.	0.6305E+04	0.6251E+04	0.5815E+04	0.5768E+04	0.1004E+04	0.5098E+03
4560.	0.6321E+04	0.6164E+04	0.5786E+04	0.5745E+04	0.1091E+04	0.5188E+03
4620.	0.6283E+04	0.6113E+04	0.5740E+04	0.5702E+04	0.1164E+04	0.5250E+03
4680.	0.6239E+04	0.6076E+04	0.5735E+04	0.5723E+04	0.1243E+04	0.5326E+03
4740.	0.6251E+04	0.6128E+04	0.5734E+04	0.5719E+04	0.1334E+04	0.5389E+03
4800.	0.6228E+04	0.6064E+04	0.5701E+04	0.5688E+04	0.1413E+04	0.5461E+03
4860.	0.6183E+04	0.6015E+04	0.5662E+04	0.5650E+04	0.1497E+04	0.5530E+03
4920.	0.6159E+04	0.6078E+04	0.5668E+04	0.5652E+04	0.1599E+04	0.5598E+03
4980.	0.6155E+04	0.5999E+04	0.5651E+04	0.5638E+04	0.1762E+04	0.5675E+03
5040.	0.6113E+04	0.5950E+04	0.5613E+04	0.5600E+04	0.1937E+04	0.5737E+03
5100.	0.6070E+04	0.6015E+04	0.5603E+04	0.5586E+04	0.2095E+04	0.5821E+03

NODE NUMBER	DISTANCE (m)	TEMPERATURE PROFILES EVERY 600. SECONDS							
1	0.00000	580.75	730.86	798.43	843.14	875.42	901.75	921.86	938.93
2	0.00064	545.47	715.35	784.46	830.90	864.48	892.24	912.83	930.15
3	0.00127	510.64	695.47	770.47	818.69	853.54	882.76	903.81	921.37
4	0.00191	469.74	667.76	756.48	806.49	842.62	873.28	894.80	912.61
5	0.00254	421.34	640.18	742.47	794.31	831.70	863.82	885.80	903.85
6	0.00318	375.16	612.73	728.47	782.16	820.80	854.37	876.81	895.10
7	0.00381	331.23	585.44	714.48	770.02	809.91	844.95	867.84	886.37
8	0.00445	289.50	558.34	700.53	757.92	799.04	835.53	858.88	877.64
9	0.00508	252.07	531.45	682.66	745.83	788.18	826.14	849.92	868.93
10	0.00572	218.84	504.80	657.84	733.77	777.34	816.76	840.99	860.23
11	0.00635	187.90	473.39	633.29	721.74	766.51	807.40	832.06	851.53
12	0.00699	159.14	435.89	609.06	709.74	755.71	798.06	823.15	842.85
13	0.00762	140.88	399.82	585.17	694.34	744.92	788.74	814.25	834.19
14	0.00826	128.25	365.22	561.60	672.85	734.16	779.44	805.37	825.53
15	0.00889	118.92	332.11	538.34	651.45	723.43	770.16	796.50	816.89
16	0.00953	111.01	300.60	515.35	630.14	712.72	760.90	787.65	808.26
17	0.01016	104.40	271.21	488.28	608.93	702.05	751.67	778.81	799.65
18	0.01080	100.01	244.48	455.86	587.82	688.37	742.45	769.99	791.05

19	0.01143	96.90	220.03	424.40	566.84	669.31	733.26	761.19	782.46
20	0.01207	94.29	196.33	393.93	545.99	650.36	724.09	752.40	773.89
21	0.01270	91.72	173.26	364.45	525.28	631.54	714.94	743.63	765.33
22	0.01334	89.31	155.08	335.99	504.74	612.85	705.82	734.87	756.79
23	0.01397	87.06	141.97	308.55	480.49	594.31	694.12	726.13	748.27
24	0.01461	84.97	132.53	282.11	451.33	575.93	677.79	717.41	739.76
25	0.01524	83.03	125.00	257.68	423.04	557.73	661.53	708.71	731.27
26	0.01588	81.23	119.12	235.15	395.66	539.71	645.32	697.55	722.79
27	0.01651	79.57	113.96	214.42	369.20	521.90	629.17	681.97	714.33
28	0.01715	77.98	109.44	194.18	343.65	504.31	613.09	666.45	705.90
29	0.01778	76.45	105.47	174.30	318.97	483.65	597.07	650.97	695.07
30	0.01842	75.00	101.96	158.21	295.13	459.17	581.12	635.55	679.96
31	0.01905	73.61	99.74	146.23	272.87	435.79	565.25	620.18	664.90
32	0.01969	72.29	98.12	137.57	252.14	413.54	549.46	604.88	649.88
33	0.02032	71.04	96.59	130.58	232.84	392.41	533.76	589.63	634.93
34	0.02096	69.86	95.15	124.93	214.94	372.35	518.17	574.44	620.02
35	0.02159	68.75	93.79	120.34	197.31	353.35	502.68	559.31	605.17
36	0.02223	67.70	92.51	116.53	179.90	335.38	484.40	544.25	590.38
37	0.02286	66.72	91.30	113.09	165.75	318.45	462.38	529.26	575.65
38	0.02350	65.81	90.16	110.04	154.48	302.57	440.97	514.33	560.98
39	0.02413	64.97	89.10	107.36	146.40	287.69	420.20	496.64	546.37
40	0.02477	64.19	88.10	105.03	140.86	274.73	400.06	475.09	531.82
41	0.02540	63.48	87.17	103.04	137.25	263.47	380.54	453.85	517.34
42	0.11740	34.36	53.27	67.44	87.35	149.15	248.82	349.61	437.07
43	0.11804	33.69	52.39	66.43	85.70	138.86	230.20	328.77	416.02
44	0.11867	33.05	51.54	65.45	84.12	130.26	212.74	308.42	395.38
45	0.11930	32.43	50.71	64.49	82.63	123.12	195.36	288.57	375.15
46	0.11994	31.84	49.91	63.56	81.21	117.25	178.00	269.71	355.33
47	0.12057	31.28	49.13	62.66	79.87	111.94	163.39	251.80	335.92
48	0.12121	30.73	48.37	61.77	78.56	107.14	151.24	234.83	316.93
49	0.12184	30.21	47.62	60.91	77.29	102.78	141.71	218.77	298.35
50	0.12248	29.71	46.90	60.07	76.05	99.95	134.22	203.60	280.58
51	0.12311	29.24	46.20	59.26	74.85	97.86	127.79	188.40	263.60
52	0.12375	28.78	45.51	58.46	73.67	95.86	122.29	173.15	247.40
53	0.12438	28.34	44.84	57.69	72.53	93.95	117.62	160.20	231.95
54	0.12502	27.93	44.19	56.94	71.42	92.13	113.32	149.71	217.23
55	0.12565	27.53	43.56	56.20	70.34	90.39	109.36	141.29	203.25
56	0.12629	27.16	42.95	55.49	69.28	88.73	105.70	134.48	189.16
57	0.12692	26.80	42.35	54.79	68.26	87.13	102.38	128.53	174.95
58	0.12756	26.45	41.77	54.12	67.26	85.61	100.00	123.38	162.73
59	0.12819	26.13	41.21	53.46	66.29	84.15	98.24	118.96	152.31
60	0.12883	25.82	40.67	52.83	65.34	82.76	96.69	114.87	143.86
61	0.12946	25.53	40.15	52.21	64.42	81.42	95.13	111.08	137.04
62	0.13010	25.25	39.64	51.61	63.52	80.15	93.61	107.56	131.06
63	0.13073	24.99	39.15	51.02	62.65	78.92	92.13	104.28	125.79
64	0.13137	24.75	38.67	50.46	61.80	77.73	90.70	101.22	121.15
65	0.13200	24.52	38.22	49.91	60.97	76.56	89.32	99.16	117.07
66	0.13264	24.30	37.78	49.37	60.17	75.41	87.97	97.60	113.25
67	0.13327	24.09	37.35	48.85	59.39	74.30	86.67	96.08	109.69
68	0.13391	23.90	36.95	48.33	58.63	73.21	85.40	94.61	106.37
69	0.13454	23.73	36.56	47.83	57.89	72.14	84.17	93.17	103.28
70	0.13518	23.56	36.18	47.34	57.17	71.11	82.97	91.77	100.36
71	0.13581	23.41	35.82	46.86	56.46	70.10	81.81	90.40	98.39
72	0.13645	23.27	35.48	46.40	55.78	69.11	80.68	89.05	96.88
73	0.13708	23.14	35.15	45.94	55.12	68.16	79.59	87.74	95.40
74	0.13772	23.02	34.84	45.49	54.48	67.22	78.51	86.45	93.95
75	0.13835	22.91	34.54	45.06	53.85	66.32	77.45	85.19	92.52
76	0.13899	22.82	34.26	44.63	53.24	65.43	76.40	83.95	91.11
77	0.13962	22.73	33.99	44.22	52.65	64.57	75.36	82.74	89.72
78	0.14026	22.65	33.73	43.81	52.07	63.74	74.34	81.55	88.35
79	0.14089	22.59	33.49	43.42	51.51	62.93	73.34	80.38	87.00
80	0.14153	22.53	33.27	43.04	50.97	62.14	72.35	79.24	85.67
81	0.14216	22.49	33.05	42.66	50.44	61.37	71.37	78.10	84.37
82	0.14280	22.45	32.86	42.30	49.92	60.62	70.40	76.98	83.08

B.5. FORTRAN source code for TRACE program.

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C      *****
C      * TRACE - Temperature Rise Across Construction Elements *
C      *      Simulation of 1-Dimentional Heat Transfer through *
C      *      Multi-Layered Construction Assemblies, e.g. LSF Walls/Floors *
C      * *
C      * The description of the basic algorithm and assumptions is provided in *
C      * "A Treatise on Theoretical Fire Endurance Rating", by Harmathy T. Z., *
C      * ASTM STP No.301, 1961, pp.10-40, and in *
C      * "A Model for Predicting Heat Transfer Through Noninsulated Unloaded *
C      * Steel-Stud Gypsum Board Wall Assemblies Exposed to Fire", by Mohamed A. *
C      * Sultan, Fire Technology, Vol. 32, No.3, 1996, pp.239-259. *
C      * *
C      * Thermal properties calibrated for Type C 12.7-mm thick gypsum board, *
C      * rock fibre, glass fibre and cellulose fibre insulation. *
C      * *
C      * Provision for user-specified fall-off (spalling) time for any layer is *
C      * implemented *
C      * *
C      * Heat flux output implemented *
C      * *
C      * Temperature profiles output implemented *
C      * *
C      * BY FARID ALFAWAKHIRI - LAST REVISED ON August 17, 2000 *
C      *****
C
C      IMPLICIT REAL*8 (A-H,O-Z)
C      CHARACTER INPUT*80, OUTPUT*80
C      COMMON/SET2/ ITOM(10),ISOM(10),DML(10),NODX(10),EMI(10),TFAL(10)
C      COMMON/SET3/ D(1000), DX(10), NB(11)
C      COMMON/SET4/ C(1000),CL(1000),SK(1000),PC(1000),SCR(1000)
C      COMMON/SET5/ SKL(10),PCL(10),BC(11)
C      COMMON/SET7/ QIN(1000),QOUT(1000),PRFL(20,1000)
C      COMMON/SET8/ TQ(2000),BQIN(2000,11)
C
C      Specify input and output files
C
C      WRITE (*,1000)
1000 FORMAT (2X,'Program TRACE - Temperature Rise Across Construction',
1          X,'Elements')
C      WRITE (*,1001)
1001 FORMAT (2X,'ENTER THE NAME OF THE INPUT FILE:',$)
C      READ (*,1003) INPUT
C      WRITE (*,1002)
1002 FORMAT (2X,'ENTER THE NAME OF THE OUTPUT FILE:',$)
C      READ (*,1003) OUTPUT
1003 FORMAT (1A80)
C
C      Open input and output files
C
C      CLOSE (9)
C      CLOSE (7)
C      OPEN (9,FILE=INPUT,STATUS='OLD')
C      OPEN (7,FILE=OUTPUT,STATUS='NEW')
C
C      Read the input file and echo to the output file
C
C      CALL DATAIN (TMAX, TS, OTS, IOFT, EMIF, AC, NOL, PRTS)
C
C      Discretize the multi-layered construction assembly and identify the nodes
C
C      CALL NODES (NOL,NOND,NOB)
C
C      Specify initial (ambient) temperature for all nodes and fire exposure

```

```

C      C  = initial node temperature for a given time step , deg.C
C      (node temperature at the end of previous time step)
C      FC  = fire (furnace) temperature, deg.C
C
C      DO 101 I=1,NOND
C      C(I)= AC
101 CONTINUE
C      FC=AC
C
C      Specify initial parameters
C      T    = time (in seconds)
C      TOUT = printout time (in seconds)
C      IQ   = indicator (order #) for output times and heat flux data record
C      TQ   = array containing output times
C      IRP  = indicator (order number) for temperature profile record
C      POUT = temperature profile printout time (in seconds)
C      IEXP = indicator of the exposed material layer
C      NOTS = number of time steps
C      RMIN = smallest stability criterion whithin a printout time step
C
C      T=0.
C      TOUT=OTS
C      IQ=1
C      TQ(1)=0.
C      IPR=0
C      POUT=PRTS
C      IEXP=1
C      NOTS=TMAX/TS
C      RMIN=99.
C
C      Specify the initial heat flow at boundary nodes
C      Specify the initial temperatures at boundary nodes and write them to the
C      output file.
C      BC  = boundary node temperature, deg.C
C      BQIN = heat flux at a boundary node, W/sq.m.
C
C      DO 102 I=1,NOB
C      BQIN(1,I)=0.
C      BC(I)=C(NB(I))
102 CONTINUE
C      WRITE (7,1004) T, FC, (BC(I),I=1,NOB)
1004 FORMAT (1X,F7.0,F7.1,<NOB>F7.1)
C
C      Do repeated operations at every time increment step (open time loop)
C
C      DO 111 ITS=1,NOTS
C      T=ITS*TS
C
C      Calculate the thermal properties at the nodes in all material layers.
C
C      DO 121 IL=IEXP,NOL
C      IF (ITOM(IL).EQ.3) GO TO 122
C
C      IF (ITOM(IL).NE.1) GO TO 123
C      CALL GYPSUM (IL)
C      GO TO 122
C
C      123 IF (ITOM(IL).NE.2) GO TO 124
C      CALL INSLTN (IL)
C      GO TO 122
C
C      124 IF (ITOM(IL).NE.4) GO TO 125
C      CALL WOOD (IL)
C      GO TO 122
C
C      125 IF (ITOM(IL).NE.5) GO TO 127
C      CALL CONCRT (IL)
C      GO TO 122

```

```

C
  127 WRITE (*,1021) ITOM(IL), IL
1021 FORMAT (5X,'UNKNOWN TYPE',I3, 2X,'OF MATERIAL LAYER',I3)
      STOP
C
  122 CONTINUE
  121 CONTINUE
C
C      Calculate the radiation heat transfer coefficient HRF and the
C      convection heat transfer coefficient HCF at the fire exposed boundary.
C      Then calculate the temperature at the first fire exposed node.
C      Dummy parameters: N (node number), HF, SKA, PCA
C      QIN = heat flux to the node zone in the current time step, W/sq.m
C      QOUT= heat flux from the node zone in the current time step, W/sq.m
C      C1 = node temperature in the current time step, deg.C
C      SCR = stability criterion at a node (in seconds)
C
      N=NB(IEXP)
      HRF=5.669E-8*EMIF*EMI(IEXP)*((FC+273.17)**2.+(C(N)+
1      273.17)**2.)*(FC+C(N)+546.34)
C
      HCF=0.95*(FC-C(N))**0.33
C
      HF=HRF+HCF
      SKA=(SK(N)+SK(N+1))/(2.*DX(IEXP))
      PCA=0.5*PC(N)*DX(IEXP)
      QIN(N)=HF*(FC-C(N))
      QOUT(N)=SKA*(C(N)-C(N+1))
      C1(N)=C(N)+(QIN(N)-QOUT(N))*TS/PCA
      SCR(N)=PCA/(HF+SKA)
C
C      Calculate the temperatures at other nodes (except last node) in the first
C      fire exposed material layer
C      Dummy parameters: N (node number), DX2, SK1, SK2, PCA
C
      DX2=2.*DX(IEXP)
      DO 113 I=1,NODX(IEXP)-2
        N=N+1
        SK1=(SK(N-1)+SK(N))/DX2
        SK2=(SK(N)+SK(N+1))/DX2
        PCA=PC(N)*DX(IEXP)
        QIN(N)=SK1*(C(N-1)-C(N))
        QOUT(N)=SK2*(C(N)-C(N+1))
        C1(N)=C(N)+(QIN(N)-QOUT(N))*TS/PCA
        SCR(N)=PCA/(SK1+SK2)
113 CONTINUE
        N=N+1
        SK1=(SK(N-1)+SK(N))/DX2
        SK2=(SK(N)+SKL(IEXP))/DX2
        PCA=PC(N)*DX(IEXP)
        QIN(N)=SK1*(C(N-1)-C(N))
        QOUT(N)=SK2*(C(N)-C(N+1))
        C1(N)=C(N)+(QIN(N)-QOUT(N))*TS/PCA
        SCR(N)=PCA/(SK1+SK2)
C
C      Similarly, calculate the temperatures at all nodes in the remaining layers
C      (open material layer loop), except the last node at the last boundary.
C      Dummy parameters: N (node number), SK1, SK2, PCA, HRC, HCC, HC, SKA
C
      DO 114 IL=IEXP+1,NOL
        N=NB(IL)
C
        IF (ITOM(IL).EQ.3) GO TO 115
        IF (ITOM(IL-1).EQ.3) GO TO 117
C
        SK1=(SK(N-1)+SKL(IL-1))/(2.*DX(IL-1))
        SK2=(SK(N)+SK(N+1))/(2.*DX(IL))
        PCA=(PCL(IL-1)*DX(IL-1)+PC(N)*DX(IL))/2.

```

```

      QIN(N)=SK1*(C(N-1)-C(N))
      QOUT(N)=SK2*(C(N)-C(N+1))
      C1(N)=C(N)+(QIN(N)-QOUT(N))*TS/PCA
      SCR(N)=PCA/(SK1+SK2)
C
117  DX2=DX(IL)*2.
      DO 118 I=1,NODX(IL)-2
      N=N+1
      SK1=(SK(N-1)+SK(N))/DX2
      SK2=(SK(N)+SK(N+1))/DX2
      PCA=PC(N)*DX(IL)
      QIN(N)=SK1*(C(N-1)-C(N))
      QOUT(N)=SK2*(C(N)-C(N+1))
      C1(N)=C(N)+(QIN(N)-QOUT(N))*TS/PCA
      SCR(N)=PCA/(SK1+SK2)
118  CONTINUE
      N=N+1
      SK1=(SK(N-1)+SK(N))/DX2
      SK2=(SK(N)+SKL(IL))/DX2
      PCA=PC(N)*DX(IL)
      QIN(N)=SK1*(C(N-1)-C(N))
      QOUT(N)=SK2*(C(N)-C(N+1))
      C1(N)=C(N)+(QIN(N)-QOUT(N))*TS/PCA
      SCR(N)=PCA/(SK1+SK2)
C
      GO TO 120
C
115  HRC=5.669E-8*EMI(IL)*((C(N)+273.17)**2.+(C(N+1)+273.17)**2.)*
1      (C(N)+C(N+1)+546.34)
      HCC=1.6*((C(N)-C(N+1))*0.33)
      HC=HRC+HCC
      SKA=(SK(N-1)+SKL(IL-1))/(2.*DX(IL-1))
      PCA=0.5*PCL(IL-1)*DX(IL-1)
      QIN(N)=SKA*(C(N-1)-C(N))
      QOUT(N)=HC*(C(N)-C(N+1))
      C1(N)=C(N)+(QIN(N)-QOUT(N))*TS/PCA
      SCR(N)=PCA/(HC+SKA)
C
      N=N+1
      SKA=(SK(N)+SK(N+1))/(2.*DX(IL+1))
      PCA=0.5*PC(N)*DX(IL+1)
      QIN(N)=HC*(C(N-1)-C(N))*CHL(IL)
      QOUT(N)=SKA*(C(N)-C(N+1))
      C1(N)=C(N)+(QIN(N)-QOUT(N))*TS/PCA
      SCR(N)=PCA/(HC+SKA)
C
120  CONTINUE
114  CONTINUE
C
      Compute the radiation and convection heat transfer coefficients, HRA and
      HCA, respectively, at the ambient side. Then compute the temperature at
      last node of the last material layer.
      Dummy parameters: N (node number), HA, SKA, PCA
C
      HRA=5.669E-8*EMI(NOL)*((AC+273.17)**2.+(C(NOND)+273.17)**2.)*
1      (AC+C(NOND)+546.34)
C
      HCA=1.1*((C(NOND)-AC)*0.25)
C
      N=NOND
      HA=HRA+HCA
      SKA=(SK(N-1)+SKL(NOL))/(2.*DX(NOL))
      PCA=0.5*PCL(NOL)*DX(NOL)
      QIN(N)=SKA*(C(N-1)-C(N))
      QOUT(N)=HA*(C(N)-AC)
      C1(N)=C(N)+(QIN(N)-QOUT(N))*TS/PCA
      SCR(N)=PCA/(HA+SKA)
C

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```

C      Check the stability criteria at all nodes
C      NMIN = the node, at which the RMIN occurred
C      TMIN = time at which RMIN occurred (in seconds)
C
      DO 131 I=1,NOND
      IF (SCR(I).GE.TS) GO TO 132
C
      WRITE (*,1031) SCR (I), I, T
      WRITE (7,1031) SCR (I), I, T
1031 FORMAT (/2X,'STABILITY CRITERION',F13.9,2X,'AT NODE',I4,2X,
1      'AT TIME',F11.5,/2X,'LESS THAN TIME STEP')
      GO TO 199
C
132 IF (SCR(I).GE.RMIN) GO TO 131
      RMIN=SCR(I)
      NMIN=I
      TMIN=T
C
131 CONTINUE
C
      Update the node temperatures at the current time step
C
      DO 135 I=NB(IEXP),NOND
      C(I)=C1(I)
135 CONTINUE
C
      Calculate the fire (furnace) temperature at the current time step
C
      CALL FIRE (IOFT,T,AC,FC)
C
      Check for printout time
C
      IF (TOUT.GT.T) GO TO 151
C
      Record to memory heat flux at boundary nodes.
C      Print out the boundary temperatures and RMIN with associated node and time
C      Also show RMIN with associated node and time on the screen.
C
      IQ=IQ+1
      TQ(IQ)=T
      IF (IEXP.EQ.1) GO TO 143
      DO 142 I=1,IEXP-1
      BC(I)=FC
      BQIN(IQ,I)=0.
      BQOT(IQ,I)=0.
C
142 CONTINUE
C
143 DO 144 I=IEXP,NOL+1
      BC(I)=C(NB(I))
      BQIN(IQ,I)=QIN(NB(I))
      BQOT(IQ,I)=QOUT(NB(I))
C
144 CONTINUE
C
      WRITE (7,1041) T, FC, (BC(I),I=1,NOB), RMIN, NMIN, TMIN
1041 FORMAT (1X,F7.0,F7.1,<NOB>F7.1,F10.5,X,I5,F11.3)
      WRITE (*,1042) RMIN, NMIN, TMIN
1042 FORMAT (5X,F13.9,I8,F13.5)
      TOUT=TOUT+OTS
      RMIN=99.
C
      Check for temperature profile printout time
C
151 IF (POUT.GT.T) GO TO 181
      IF (IPR.GE.20) GO TO 181
C
      Record to memory temperature profiles.
C
      IPR=IPR+1

```

```

        IF (IEXP.EQ.1) GO TO 153
        DO 152 J=1,NB(IEXP)-1
          PRFL(IPR,J)=FC
152 CONTINUE
C
153 DO 154 J=NB(IEXP),NOND
    PRFL(IPR,J)=C(J)
154 CONTINUE
    POUT=POUT+PRTS
C
C      Check the material layers for fall-off time and update IEXP.
C      Dummy parameter NFAL (number of fallen-off material layers).
C
181  NFAL=0
    DO 182 I=IEXP,NOL
      IF (T.LT.TFAL(I)) GO TO 183
      NFAL=NFAL+1
183 CONTINUE
182 CONTINUE
    IEXP=IEXP+NFAL
C
C      Close the time loop
C
111 CONTINUE
C
C      Printout the heat flux data for boundary nodes
C
      WRITE (7,1054) (NB(I),I=1,NOB)
1054 FORMAT (/7X,'TIME',4X,'HEAT FLUX (W/sq.m.) AT BOUNDARY NODES',
1      /8X,'sec.',X,<NOB>I12)
C
      DO 158 J=1,IQ
        WRITE (7, 1053) TQ(J), (BQIN(J,I),I=1,NOB)
1053 FORMAT (5X,F7.0,2X,<NOB>E12.4)
158 CONTINUE
C
C      Printout the temperature profiles
C
      IF (TMAX.LT.PRTS) GO TO 199
      WRITE (7,1052) PRTS
1052 FORMAT (/7X,'NODE',3X,'DISTANCE',3X,'TEMPERATURE PROFILES EVERY',
1      F7.0,2X,'SECONDS',
2      /5X,'NUMBER',7X,'(m)')
      DO 157 J=1,NOND
        WRITE (7,1051) J, D(J), (PRFL(I,J),I=1,IPR)
1051 FORMAT (5X,I5,F12.5,<IPR>F8.2)
157 CONTINUE
C
C
199 STOP
    END
C
C
C      *****
C      * DATAIN *
C      * READS THE INPUT FILE AND *
C      * ECHOES TO THE OUTPUT FILE *
C      *****
C
      SUBROUTINE DATAIN (TMAX, TS, OTS, IOFT, EMIF, AC, NOL, PRTS)
C
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION TITLE(20)
      COMMON/SET2/ ITOM(10),ISOM(10),DML(10),NODX(10),EMI(10),TFAL(10)
C
      Problem identification
C
      READ (9,2001) TITLE

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```

2001 FORMAT (20A4)
      WRITE (7,2002) TITLE
2002 FORMAT (1H1/,2X,20A4)
C
C      Read and echo to the output
C      TMAX = total time of fire-exposure simulation (in seconds)
C      TS   = time increment step (in seconds)
C            TS should be smaller than (numerical) stability criterion SCR at
C            any node at any time during the simulation; the program computes
C            SCR at all nodes at every time step and determines the minimum SCR
C            during every OTS period; if this minimum SCR is smaller than TS -
C            the program will stop execution and display the error message on
C            the screen
C      OTS  = time step (in seconds) for writing boundary temperatures (i.e.
C            temperatures at boundaries of all material layers) to output file,
C            e.g. enter 60. for 1-minute intervals
C            the program will also write to the output file the minimum SCR for
C            each OTS period (and the node and time for this minimum SCR)
C            the program will also write to the output file the heat flux at
C            for every boundary node
C      IOFT = indicator of fire type
C            1 for ASTM E119 time-temperature curve (approximated formula)
C            2 for ISO 834 time-temperature curve
C      EMIF = emissivity of fire
C      AC   = ambient temperature (in degrees C)
C      NOL  = number of material layers in the wall assembly (cavity counts as
C            layer); current dimension of the program limits NOL to 10
C      PRTS = time step (in seconds) for writing all node temperatures to output
C            file, e.g. enter 300. for 5-min. time intervals;
C            enter value larger than TMAX if no temp. profiles desired in output
C            current dimension limits the number of profiles to 20
C
      READ (9,*) TMAX, TS, OTS, IOFT, EMIF, AC, NOL, PRTS
      WRITE (7,2003) TMAX, TS, OTS, IOFT, EMIF, AC, NOL, PRTS
2003 FORMAT (/5X,'DURATION OF THE SIMULATION'   =',F12.0/5X,
1         'TIME INCREMENT STEP'               =',F12.5/5X,
2         'OUTPUT TIME STEP'                   =',F12.0/5X,
3         'TIME-TEMPERATURE CURVE TYPE'        =',I12 /5X,
4         'EMISSIVITY OF FIRE'                 =',F12.3/5X,
5         'AMBIENT TEMPERATURE'                =',F12.2/5X,
6         'NUMBER OF MATERIAL LAYERS'          =',I12 /5X,
7         'TEMP. PROFILE OUTPUT TIME STEP'     =',F12.0  )
C
C      Read for every material layer in the assembly
C      The input parameters for material layers (1 line per layer) should
C      be listed in sequence starting with the first line for the fire-exposed
C      material layer and ending with the line for material layer on the
C      ambient side;
C      current dimension limits the number of material layers to 10
C      ITOM = indicator for type of material
C            1 for gypsum board (currently has subtypes 1-6)
C            2 for insulation (currently has subtypes 1-7)
C            3 for cavity (no subtypes)
C            4 for wood products (currently has subtype 1)
C            5 for concrete (currently has subtype 1)
C      ISOM = indicator for subtype of material
C            1 for Type X gypsum board with properties according to
C              Sultan (1996)
C            6 calibrated for Type C gypsum board, 12.7 mm thick
C            4 calibrated for insulation made of cellulose fibres treated with
C              fire retardants (dry blown, loose fill, bulk density 47 kg/cu.m)
C            5 calibrated for rock fibre insulation (bulk density 33 kg/cu.m)
C            7 calibrated for glass fibre insulation (bulk density 10 kg/cu.m)
C            Subtypes 2-5 for gypsum board, subtypes 1-3 & 6 for insulation,
C            subtype 1 for wood products, and subtype 1 for concrete are
C            currently used for parametric studies.
C      DML  = thickness of material layer (in meters)
C      NODX = number of discretization layers (elements) for the material layer

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C          enter 1 (or any other integer) for cavity material layers
C          currently the dimension of the program limits the total number of
C          elements in the assembly to 999
C          EMI = emissivity of the material layer surface
C          enter any real number for cavity layers
C          TFAL = time of fall-off (in seconds)
C          the program removes the material layer from the assembly when the
C          time of fall-off is reached in the simulation
C
C
C          DO 201 I=1,NOL
C          CHL(I)=1.0
C          READ (9,*) ITOM(I), ISOM(I), DML(I), NODX(I), EMI(I), TFAL(I)
201 CONTINUE
C
C          Check the input data.
C          The first and last material layers cannot be cavities.
C          If a material layer is cavity, the layer before and the layer after must
C          be solid materials.
C          The fall-off time of a material layer cannot be smaller than the fall-off
C          time of any material layer that is closer to fire (i.e. fall-off can
C          develop only in sequence starting from the fire exposed side).
C          The cavity layer cannot be discretized (NODX=1).
C          The emissivity of the cavity layer is assigned to be the combined
C          emissivity of the parallel surfaces of the solid material layers before
C          and after the cavity layer.
C          The fall-off time of the cavity layer must be equal to the fall-off time
C          of the previous solid material layer.
C          Dummy parameter: LA (layer after).
C
C          IF (ITOM(1).NE.3) GO TO 212
C          WRITE (*,2011)
2011  FORMAT (/5X,'INPUT ERROR : LAYER 1 CANNOT BE OF TYPE 3 (CAVITY)')
C          GO TO 298
C
C          212 IF (ITOM(NOL).NE.3) GO TO 213
C          WRITE (*,2012)
2012  FORMAT (/5X,'INPUT ERROR : LAST LAYER CANNOT BE OF TYPE 3',X,
1      ' (CAVITY)')
C          GO TO 298
C
C          DO 218 I=2,NOL
C          IF (TFAL(I).GE.TFAL(I-1)) GO TO 219
C          TFAL(I)=TFAL(I-1)
219 CONTINUE
218 CONTINUE
C
C          213 IF (NOL.LE.2) GO TO 221
C          DO 214 I=2,NOL-1
C          IF (ITOM(I).NE.3) GO TO 215
C          IF (ITOM(I+1).NE.3) GO TO 217
C          LA=I+1
C          WRITE (*,2013) I, LA
2013  FORMAT (/5X,'INPUT ERROR : LAYERS',I2,X,'AND',I2,X,'ARE TWO
1      CONSECUTIVE CAVITY LAYERS')
C          GO TO 298
217  NODX(I)=1
C          CHL(I)=EMI(I)
C          EMI(I)=1./(1./EMI(I-1)+1./EMI(I+1)-1.)
C          TFAL(I)=TFAL(I-1)
C
C          215 CONTINUE
214 CONTINUE
C
C          Echo the input data to the output file.
C
C          221 DO 222 I=1,NOL
C          WRITE (7,2022) I,ITOM(I),ISOM(I),DML(I),NODX(I),EMI(I),TFAL(I)

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2022 FORMAT (/5X,'LAYER NUMBER',I12 /5X,
1          'TYPE OF MATERIAL',I12 /5X,
2          'SUBTYPE OF MATERIAL',I12 /5X,
3          'THICKNESS',F12.4/5X,
4          'NUMBER OF (dx) ELEMENTS',I12 /5X,
5          'EMISSIVITY',F12.3/5X,
6          'FALL-OFF TIME',F12.0 )
222 CONTINUE
C
C      Close the input file
C
C      CLOSE (9)
C      GO TO 299
C
298 STOP
C
C
299 RETURN
END
C
C
C      *****
C      * NODES *
C      * DISCRETIZES THE WALL SYSTEM *
C      * IDENTIFYES THE NODES *
C      *****
C
SUBROUTINE NODES (NOL,NOND,NOB)
C
C      IMPLICIT REAL*8 (A-H,O-Z)
C      COMMON/SET2/ ITOM(10),ISOM(10),DML(10),NODX(10),EMI(10),TFAL(10)
C      COMMON/SET3/ D(1000), DX(10), NB(11)
C
C      In each material layer, compute the distance increment DX (for
C      discretization to smaller finite layers), discretize the material layer
C      to finite layers, assign numbers to nodes consequently and determine the
C      distances D from the initial fire exposed surface for each node.
C      Identify the boundary nodes NB, then calculate the total number of nodes
C      NOND and the total number of boundaries NOB.
C      D = node distance from the initial fire exposed surface.
C      DX = thickness of the discretization layers in a material layer.
C      NB = array containing the numbers of the boundary nodes.
C      Dummy parameters: N (node number), DIST (distance from initial fire
C      exposed surface)
C
C      DIST=0.
C      N=0
C      DO 301 I=1,NOL
C      N=N+1
C      D(N)=DIST
C      DX(I)=DML(I)/NODX(I)
C      DIST=DIST+DX(I)
C      NB(I)=N
C      IF (ITOM(I).EQ.3) GO TO 302
C
C      DO 303 J=1,NODX(I)-1
C      N=N+1
C      D(N)=DIST
C      DIST=DIST+DX(I)
303 CONTINUE
C
302 CONTINUE
301 CONTINUE
C      N=N+1
C      D(N)=DIST
C      NB(NOL+1)=N
C      NOND=N
C      NOB=NOL+1

```

```

C
      WRITE (7,3031) NOND, NOB
3031 FORMAT (/5X,'TOTAL NUMBER OF NODES      ',I4 /5X,
1          'TOTAL NUMBER OF BOUNDARIES      ',I4 /5X)
C
      WRITE (7,3032) (NB(I),I=1,NOB)
3032 FORMAT (/3X,'TIME',2X,'FIRE  ',2X,'BOUNDARY NODES',<7*NOB-18>X,
1          1X,'MIN.STABILITY',2X,'AT',5X,'AT',
2          /4X,'sec.',2X,'deg.C',<NOB>I7,2X,'CRITERION',2X,'NODE',
2          3X,'TIME')
C
C
      RETURN
      END
C
C
C
C *****
C * FIRE *
C * COMPUTES THE FIRE TEMPERATURE *
C *****
C
      SUBROUTINE FIRE (IOFT,T,AC,FC)
C
      IMPLICIT REAL*8 (A-H,O-Z)
C
      IF (IOFT.EQ.2) GO TO 402
C
      Compute the ASTM E119 fire temperature at time T (in seconds)
C
      DUM=DSQRT(T/60.)
      FC=AC+750.*(1.-DEXP(-0.49*DUM))+22.*DUM
      GO TO 410
C
      Compute the ISO 834 fire temperature at time T (in seconds)
C
402  FC=AC+345.*DLOG10(8.*T/60.+1.)
C
410  CONTINUE
C
      RETURN
      END
C
C
C
C *****
C * GYPSUM *
C * COMPUTES THERMAL PROPERTIES *
C * FOR NODES IN GYPSUM LAYERS *
C *****
C
      SUBROUTINE GYPSUM (IL)
C
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON/SET2/ ITOM(10),ISOM(10),DML(10),NODX(10),EMI(10),TFAL(10)
      COMMON/SET3/ D(1000), DX(10), NB(11)
      COMMON/SET4/ C(1000),C1(1000),SK(1000),PC(1000),SCR(1000)
      COMMON/SET5/ SKL(10),PCL(10),BC(11)
C
      Specify the first node NF and last node NL in the material layer
C
      NF=NB(IL)
      NL=NB(IL)+NODX(IL)
C
      Depending on subtype ISOM of material, calculate the thermal properties
C
      SK = thermal conductivity (in W/m/deg.C)
      PC = heat capacity (in J/cu.m/deg.C)
      SKL = SK of the last node in a material layer

```

```

C      PCL = PC of the last node in a material layer
C
501  IF (ISOM(IL).NE.1) GO TO 502
      DO 511 N=NF,NL
          SK(N)=SKG1(C(N))
          PC(N)=PCG1(C(N))
511  CONTINUE
      SKL(IL)=SK(NL)
      PCL(IL)=PC(NL)
      GO TO 599
C
502  IF (ISOM(IL).NE.2) GO TO 503
      DO 512 N=NF,NL
          SK(N)=SKG2(C(N))
          PC(N)=699.*CG2(C(N))
512  CONTINUE
      SKL(IL)=SK(NL)
      PCL(IL)=PC(NL)
      GO TO 599
C
503  IF (ISOM(IL).NE.3) GO TO 504
      DO 513 N=NF,NL
          SK(N)=SKG3(C(N))
          PC(N)=PCG1(C(N))
513  CONTINUE
      SKL(IL)=SK(NL)
      PCL(IL)=PC(NL)
      GO TO 599
C
504  IF (ISOM(IL).NE.4) GO TO 505
      DO 514 N=NF,NL
          SK(N)=SKG2(C(N))
          PC(N)=654.*CG2(C(N))
514  CONTINUE
      SKL(IL)=SK(NL)
      PCL(IL)=PC(NL)
      GO TO 599
C
505  IF (ISOM(IL).NE.5) GO TO 506
      DO 515 N=NF,NL
          SK(N)=SKG2(C(N))
          PC(N)=699.*CG3(C(N))
515  CONTINUE
      SKL(IL)=SK(NL)
      PCL(IL)=PC(NL)
      GO TO 599
C
C      ISOM=6 calibrated for Type C gypsum board 12.7 mm thick
C
506  IF (ISOM(IL).NE.6) GO TO 598
      DO 516 N=NF,NL
          SK(N)=SKG4(C(N))
          PC(N)=700.*CG4(C(N))
516  CONTINUE
      SKL(IL)=SK(NL)
      PCL(IL)=PC(NL)
      GO TO 599
C
598  WRITE (*,5001) ISOM(IL), IL
5001  FORMAT (5X,'UNKNOWN SUBTYPE',I3, 2X,'OF MATERIAL LAYER',I3)
      STOP
C
C
599  RETURN
      END
C
C
C      *****

```

```

C      * INSLTN *
C      * COMPUTES THERMAL PROPERTIES *
C      * FOR NODES IN INSULATION LAYERS *
C      *****
C
C      SUBROUTINE INSLTN (IL)
C
C      IMPLICIT REAL*8 (A-H,O-Z)
C      COMMON/SET2/ ITOM(10),ISOM(10),DML(10),NODX(10),EMI(10),TFAL(10)
C      COMMON/SET3/ D(1000), DX(10), NB(11)
C      COMMON/SET4/ C(1000),Cl(1000),SK(1000),PC(1000),SCR(1000)
C      COMMON/SET5/ SKL(10),PCL(10),BC(11)
C
C      Specify the first node NF and the last node NL in the material layer
C
C      NF=NB(IL)
C      NL=NB(IL)+NODX(IL)
C
C      Depending on subtype ISOM of material, calculate the thermal properties
C      SK = thermal conductivity (in W/m/deg.C)
C      PC = heat capacity (in J/cu.m/deg.C)
C      SKL = SK of the last node in a material layer
C      PCL = PC of the last node in a material layer
C
C      501 IF (ISOM(IL).NE.1) GO TO 502
C          DO 511 N=NF,NL
C              SK(N)=SKI1(C(N))
C              PC(N)=33000.
C      511 CONTINUE
C          SKL(IL)=SK(NL)
C          PCL(IL)=PC(NL)
C          GO TO 599
C
C      502 IF (ISOM(IL).NE.2) GO TO 503
C          DO 512 N=NF,NL
C              SK(N)=SKI1(C(N))
C              PC(N)=5300.
C      512 CONTINUE
C          SKL(IL)=SK(NL)
C          PCL(IL)=PC(NL)
C          GO TO 599
C
C      503 IF (ISOM(IL).NE.3) GO TO 504
C          DO 513 N=NF,NL
C              SK(N)=SKI2(C(N))
C              PC(N)=PCI1(C(N))
C      513 CONTINUE
C          SKL(IL)=SK(NL)
C          PCL(IL)=PC(NL)
C          GO TO 599
C
C      ISOM=4 calibrated for cellulose treated with fire retardants
C
C      504 IF (ISOM(IL).NE.4) GO TO 505
C          DO 514 N=NF,NL
C              SK(N)=SKI4(C(N))
C              PC(N)=115000.
C      514 CONTINUE
C          SKL(IL)=SK(NL)
C          PCL(IL)=PC(NL)
C          GO TO 599
C
C      ISOM=5 calibrated for rock fibre insulation
C
C      505 IF (ISOM(IL).NE.5) GO TO 506
C          DO 515 N=NF,NL
C              SK(N)=SKI5(C(N))
C              PC(N)=27000.

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515 CONTINUE
    SKL(IL)=SK(NL)
    PCL(IL)=PC(NL)
    GO TO 599
C
506 IF (ISOM(IL).NE.6) GO TO 507
    DO 516 N=NF,NL
    SK(N)=SKI3(C(N))
    PC(N)=27000.
516 CONTINUE
    SKL(IL)=SK(NL)
    PCL(IL)=PC(NL)
    GO TO 599
C
C    ISOM=7 calibrated for glass fibre insulation
C
507 IF (ISOM(IL).NE.7) GO TO 598
    DO 517 N=NF,NL
    SK(N)=SKI7(C(N))
    PC(N)=9000.
517 CONTINUE
    SKL(IL)=SK(NL)
    PCL(IL)=PC(NL)
    GO TO 599
C
598 WRITE (*,5001) ISOM (IL), IL
5001 FORMAT (5X,'UNKNOWN SUBTYPE',I3, 2X,'OF MATERIAL LAYER',I3)
    STOP
C
599 RETURN
    END
C
C
C *****
C * WOOD *
C * COMPUTES THERMAL PROPERTIES *
C * FOR NODES IN WOOD LAYERS *
C *****
C
SUBROUTINE WOOD (IL)
C
    IMPLICIT REAL*8 (A-H,O-Z)
    COMMON/SET2/ ITOM(10),ISOM(10),DML(10),NODX(10),EMI(10),TFAL(10)
    COMMON/SET3/ D(1000), DX(10), NB(11)
    COMMON/SET4/ C(1000),C1(1000),SK(1000),PC(1000),SCR(1000)
    COMMON/SET5/ SKL(10),PCL(10),BC(11)
C
C    Specify the first node NF and last node NL in the material layer
C
    NF=NB(IL)
    NL=NB(IL)+NODX(IL)
C
C    Depending on subtype ISOM of material, calculate the thermal properties
C    SK = thermal conductivity (in W/m/deg.C)
C    PC = heat capacity (in J/cu.m/deg.C)
C    SKL = SK of the last node in a material layer
C    PCL = PC of the last node in a material layer
C
501 IF (ISOM(IL).NE.1) GO TO 598
    DO 511 N=NF,NL
    SK(N)=SKW1(C(N))
    PC(N)=PCW1(C(N))
511 CONTINUE
    SKL(IL)=SK(NL)
    PCL(IL)=PC(NL)
    GO TO 599
C
C

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598 WRITE (*,5001) ISOM(IL), IL
5001 FORMAT (5X,'UNKNOWN SUBTYPE',I3, 2X,'OF MATERIAL LAYER',I3)
      STOP
C
C
599 RETURN
      END
C
C
C *****
C * CONCRT *
C * COMPUTES THERMAL PROPERTIES *
C * FOR NODES IN CONCRETE LAYERS *
C *****
C
      SUBROUTINE CONCRT (IL)
C
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON/SET2/ ITOM(10),ISOM(10),DML(10),NODX(10),EMI(10),TFAL(10)
      COMMON/SET3/ D(1000), DX(10), NB(11)
      COMMON/SET4/ C(1000),C1(1000),SK(1000),PC(1000),SCR(1000)
      COMMON/SET5/ SKL(10),PCL(10),BC(11)
C
C      Specify the first node NF and last node NL in the material layer
C
      NF=NB(IL)
      NL=NB(IL)+NODX(IL)
C
C      Depending on subtype ISOM of material, calculate the thermal properties
C      SK = thermal conductivity (in W/m/deg.C)
C      PC = heat capacity (in J/cu.m/deg.C)
C      SKL = SK of the last node in a material layer
C      PCL = PC of the last node in a material layer
C
501 IF (ISOM(IL).NE.1) GO TO 598
      DO 511 N=NF,NL
          SK(N)=SKC1(C(N))
          PC(N)=PCC1(C(N))
511 CONTINUE
      SKL(IL)=SK(NL)
      PCL(IL)=PC(NL)
      GO TO 599
C
C
598 WRITE (*,5001) ISOM(IL), IL
5001 FORMAT (5X,'UNKNOWN SUBTYPE',I3, 2X,'OF MATERIAL LAYER',I3)
      STOP
C
C
599 RETURN
      END
C
C
C *****
C * THERMAL CONDUCTIVITY FOR GYPSUM *
C * FORMULA 1
C *****
C
      DOUBLE PRECISION FUNCTION SKG1(T)
C
      IMPLICIT REAL*8 (A-H,O-Z)
C
701 IF (T.GE.100.) GO TO 702
      SKG1=0.25
      GO TO 799
C
702 IF (T.GE.400.) GO TO 703
      SKG1=0.12

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      GO TO 799
C
703  IF (T.GE.800.) GO TO 704
      SKG1=-0.01+0.00035*T
      GO TO 799
C
704  SKG1=-0.77+0.0013*T
C
C
799  RETURN
      END
C
C
C *****
C * THERMAL CONDUCTIVITY FOR GYPSUM *
C * FORMULA 2 *
C *****
C
      DOUBLE PRECISION FUNCTION SKG2(T)
C
      IMPLICIT REAL*8 (A-H,O-Z)
C
701  IF (T.GE.100.) GO TO 702
      SKG2=0.23
      GO TO 799
C
702  IF (T.GE.800.) GO TO 703
      SKG2=0.15
      GO TO 799
C
703  SKG2=0.27
C
C
799  RETURN
      END
C
C
C *****
C * THERMAL CONDUCTIVITY FOR GYPSUM *
C * FORMULA 3 *
C *****
C
      DOUBLE PRECISION FUNCTION SKG3(T)
C
      IMPLICIT REAL*8 (A-H,O-Z)
C
701  IF (T.GE.200.) GO TO 702
      SKG3=0.2-0.0005*T
      GO TO 799
C
702  IF (T.GE.930.) GO TO 703
      SKG3=0.0616+0.000192*T
      GO TO 799
C
703  SKG3=-1.434+0.0018*T
C
C
799  RETURN
      END
C
C
C *****
C * THERMAL CONDUCTIVITY FOR GYPSUM *
C * FORMULA 4 (Type C 12.7 mm thick) *
C *****
C
      DOUBLE PRECISION FUNCTION SKG4(T)
C

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      IMPLICIT REAL*8 (A-H,O-Z)
C
701  IF (T.GE.100.) GO TO 702
      SKG4=0.27
      GO TO 799
C
702  IF (T.GE.200.) GO TO 703
      SKG4=0.15
      GO TO 799
C
703  IF (T.GE.500.) GO TO 704
      SKG4=0.17
      GO TO 799
C
704  IF (T.GE.700.) GO TO 705
      SKG4=0.25
      GO TO 799
C
705  IF (T.GE.800.) GO TO 706
      SKG4=0.45
      GO TO 799
C
706  SKG4=0.45
C
C
799  RETURN
      END
C
C
C *****
C * HEAT CAPACITY FOR GYPSUM          *
C * FORMULA 1                        *
C *****
C
      DOUBLE PRECISION FUNCTION PCG1(T)
C
      IMPLICIT REAL*8 (A-H,O-Z)
C
701  IF (T.GE.78.1) GO TO 702
      PCG1=698.*(6.146*T+1377.1)
      GO TO 799
C
702  IF (T.GE.85.72) GO TO 703
      PCG1=576.38*(150.*T-9857.9)
      GO TO 799
C
703  IF (T.GE.97.15) GO TO 704
      PCG1=576.38*(262.5*T-19501.5)
      GO TO 799
C
704  IF (T.GE.123.82) GO TO 705
      PCG1=576.38*(476.7*T-40311.)
      GO TO 799
C
705  IF (T.GE.139.06) GO TO 706
      PCG1=576.38*(154507.4-1096.7*T)
      GO TO 799
C
706  IF (T.GE.148.58) GO TO 707
      PCG1=576.38*(16601.3-105.*T)
      GO TO 799
C
707  IF (T.GE.373.34) GO TO 708
      PCG1=576.38*(1188.9-1.271*T)
      GO TO 799
C
708  IF (T.GE.430.48) GO TO 709
      PCG1=576.38*714.3

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      GO TO 799
C
709  IF (T.GE.571.43) GO TO 710
      PCG1=576.38*(1150.8-1.014*T)
      GO TO 799
C
710  IF (T.GE.609.52) GO TO 711
      PCG1=576.38*(1.877*T-501.2)
      GO TO 799
C
711  IF (T.GE.662.85) GO TO 712
      PCG1=576.38*(44.2*T-26300.)
      GO TO 799
C
712  IF (T.GE.670.47) GO TO 713
      PCG1=576.38*3000.
      GO TO 799
C
713  IF (T.GE.685.71) GO TO 714
      PCG1=576.38*(-150.*T+103570.)
      GO TO 799
C
714  PCG1=576.38*571.4
C
C
799  RETURN
      END
C
C
C *****
C * SPECIFIC HEAT FOR GYPSUM *
C * FORMULA 2 *
C *****
C
      DOUBLE PRECISION FUNCTION CG2(T)
C
      IMPLICIT REAL*8 (A-H,O-Z)
C
701  IF (T.GE.55.) GO TO 702
      CG2=1000.
      GO TO 799
C
702  IF (T.GE.70.) GO TO 703
      CG2=1600.
      GO TO 799
C
703  IF (T.GE.102.) GO TO 704
      CG2=727.*T-49154.
      GO TO 799
C
704  IF (T.GE.115.) GO TO 705
      CG2=163353.-1412.*T
      GO TO 799
C
705  CG2=1000.
C
C
799  RETURN
      END
C
C
C *****
C * SPECIFIC HEAT FOR GYPSUM *
C * FORMULA 3 *
C *****
C
      DOUBLE PRECISION FUNCTION CG3(T)
C

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      IMPLICIT REAL*8 (A-H,O-Z)
C
701  IF (T.GE.55.) GO TO 702
      CG3=1000.
      GO TO 799
C
702  IF (T.GE.70.) GO TO 703
      CG3=1600.
      GO TO 799
C
703  IF (T.GE.115.) GO TO 704
      CG3=12430.46
      GO TO 799
C
704 CG3=1000.
C
C
799 RETURN
      END
C
C
C *****
C * SPECIFIC HEAT FOR GYPSUM *
C * FORMULA 4 (Type C 12.7 mm thick)*
C *****
C
      DOUBLE PRECISION FUNCTION CG4(T)
C
      IMPLICIT REAL*8 (A-H,O-Z)
C
701  IF (T.GE.50.) GO TO 702
      CG4=700.
      GO TO 799
C
702  IF (T.GE.80.) GO TO 703
      CG4=1000.
      GO TO 799
C
703  IF (T.GE.100.) GO TO 704
      CG4=2000.
      GO TO 799
C
704  IF (T.GE.120.) GO TO 705
      CG4=4000.
      GO TO 799
C
705  IF (T.GE.140.) GO TO 706
      CG4=8000.
      GO TO 799
C
706  IF (T.GE.160.) GO TO 707
      CG4=13000.
      GO TO 799
C
707  IF (T.GE.180.) GO TO 708
      CG4=10000.
      GO TO 799
C
708  IF (T.GE.300.) GO TO 709
      CG4=4000.
      GO TO 799
C
709  IF (T.GE.500.) GO TO 710
      CG4=2000.
      GO TO 799
C
710  IF (T.GE.700.) GO TO 711
      CG4=700.

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```

      GO TO 799
C
711 CG4=500.
C
C
799 RETURN
    END
C
C
C *****
C * THERMAL CONDUCTIVITY FOR INSULATION *
C * FORMULA 1 *
C *****
C
DOUBLE PRECISION FUNCTION SKI1(T)
C
    IMPLICIT REAL*8 (A-H,O-Z)
C
701 IF (T.GE.400.) GO TO 702
    SKI1=0.05+0.0005*T
    GO TO 799
C
702 IF (T.GE.600.) GO TO 703
    SKI1=-0.15+0.00125*T
    GO TO 799
C
703 IF (T.GE.800.) GO TO 704
    SKI1=-0.41+0.00185*T
    GO TO 799
C
704 SKI1=-1.35+0.00315*T
C
C
799 RETURN
    END
C
C
C *****
C * THERMAL CONDUCTIVITY FOR INSULATION *
C * FORMULA 2 *
C *****
C
DOUBLE PRECISION FUNCTION SKI2(T)
C
    IMPLICIT REAL*8 (A-H,O-Z)
C
701 IF (T.GE.100.) GO TO 702
    SKI2=0.03+0.00005*T
    GO TO 799
C
702 IF (T.GE.430.) GO TO 703
    SKI2=0.0089+0.00026*T
    GO TO 799
C
703 SKI2=-0.83+0.000476*T
C
C
799 RETURN
    END
C
C
C *****
C * THERMAL CONDUCTIVITY FOR INSULATION *
C * FORMULA 3 *
C *****
C
DOUBLE PRECISION FUNCTION SKI3(T)
C

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```

      IMPLICIT REAL*8 (A-H,O-Z)
C
  701  IF (T.GE.100.) GO TO 702
      SKI3=0.5
      GO TO 799
C
  702  IF (T.GE.1500.) GO TO 703
      SKI3=0.03+0.0000005*(T+273.)**1.5+0.000000001*(T+273.)**3.
      GO TO 799
C
  703  SKI3=2.0
C
C
  799  RETURN
      END
C
C
C *****
C * THERMAL CONDUCTIVITY FOR INSULATION *
C * FORMULA 4 (cellulose) *
C *****
C
      DOUBLE PRECISION FUNCTION SKI4(T)
C
      IMPLICIT REAL*8 (A-H,O-Z)
C
  701  IF (T.GE.80.) GO TO 702
      SKI4=1.0
      GO TO 799
C
  702  IF (T.GE.200.) GO TO 703
      SKI4=0.3
      GO TO 799
C
  703  IF (T.GE.300.) GO TO 704
      SKI4=0.3
      GO TO 799
C
  704  IF (T.GE.400.) GO TO 705
      SKI4=0.3
      GO TO 799
C
  705  IF (T.GE.500.) GO TO 706
      SKI4=1.0
      GO TO 799
C
  706  IF (T.GE.700.) GO TO 707
      SKI4=1.0
      GO TO 799
C
  707  SKI4=2.0
C
C
  799  RETURN
      END
C
C
C *****
C * THERMAL CONDUCTIVITY FOR INSULATION *
C * FORMULA 5 (rock fibre) *
C *****
C
      DOUBLE PRECISION FUNCTION SKI5(T)
C
      IMPLICIT REAL*8 (A-H,O-Z)
C
  701  IF (T.GE.80.) GO TO 702
      SKI5=1.0

```

```

      GO TO 799
C
702  IF (T.GE.200.) GO TO 703
      SKI5=0.5
      GO TO 799
C
703  IF (T.GE.300.) GO TO 704
      SKI5=0.1
      GO TO 799
C
704  IF (T.GE.400.) GO TO 705
      SKI5=0.1
      GO TO 799
C
705  IF (T.GE.500.) GO TO 706
      SKI5=1.5
      GO TO 799
C
706  IF (T.GE.700.) GO TO 707
      SKI5=2.0
      GO TO 799
C
707  SKI5=3.0
C
C
799  RETURN
      END
C
C
C *****
C * THERMAL CONDUCTIVITY FOR INSULATION *
C * FORMULA 7 (glass fibre) *
C *****
C
      DOUBLE PRECISION FUNCTION SKI7(T)
C
      IMPLICIT REAL*8 (A-H,O-Z)
C
701  IF (T.GE.80.) GO TO 702
      SKI7=1.0
      GO TO 799
C
702  IF (T.GE.200.) GO TO 703
      SKI7=0.5
      GO TO 799
C
703  IF (T.GE.300.) GO TO 704
      SKI7=0.1
      GO TO 799
C
704  IF (T.GE.400.) GO TO 705
      SKI7=0.1
      GO TO 799
C
705  IF (T.GE.500.) GO TO 706
      SKI7=1.5
      GO TO 799
C
706  IF (T.GE.700.) GO TO 707
      SKI7=2.0
      GO TO 799
C
707  SKI7=3.0
C
C
799  RETURN
      END
C

```

```

C
C *****
C * HEAT CAPACITY FOR INSULATION *
C * FORMULA 1 *
C *****
C
C DOUBLE PRECISION FUNCTION PCI1(T)
C
C IMPLICIT REAL*8 (A-H,O-Z)
C
C 701 IF (T.GT.300.) GO TO 702
C     PCI1=96.*(625.+2.5*T)
C     GO TO 799
C
C 702 IF (T.GT.530.) GO TO 703
C     PCI1=96.*(1800.-1.3*T)
C     GO TO 799
C
C 703 PCI1=96.*(-1930.+5.7*T)
C
C 799 RETURN
C     END
C
C *****
C * THERMAL CONDUCTIVITY FOR WOOD *
C * FORMULA 1 (cnd. softwood plywood) *
C *****
C
C DOUBLE PRECISION FUNCTION SKW1(T)
C
C IMPLICIT REAL*8 (A-H,O-Z)
C
C 701 IF (T.GE.100.) GO TO 702
C     SKW1=0.15
C     GO TO 799
C
C 702 IF (T.GE.250.) GO TO 703
C     SKW1=0.2
C     GO TO 799
C
C 703 IF (T.GE.500.) GO TO 704
C     SKW1=0.1
C     GO TO 799
C
C 704 SKW1=0.15
C
C 799 RETURN
C     END
C
C *****
C * THERMAL CONDUCTIVITY FOR CONCRETE *
C * FORMULA 1 (density 2400 kg/cu.m) *
C *****
C
C DOUBLE PRECISION FUNCTION SKC1(T)
C
C IMPLICIT REAL*8 (A-H,O-Z)
C
C 701 IF (T.GE.200.) GO TO 702
C     SKC1=1.8
C     GO TO 799
C
C 702 IF (T.GE.500.) GO TO 703
C     SKC1=1.55

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```

      GO TO 799
C
703  IF (T.GE.800.) GO TO 704
      SKC1=1.4
      GO TO 799
C
704  SKC1=1.1
C
C
799  RETURN
      END
C
C
C *****
C * HEAT CAPACITY FOR WOOD PRODUCTS *
C * FORMULA 1 (cdn. softwood plywood) *
C *****
C
      DOUBLE PRECISION FUNCTION PCW1(T)
C
      IMPLICIT REAL*8 (A-H,O-Z)
C
701  IF (T.GT.100.) GO TO 702
      PCW1=750000.
      GO TO 799
C
702  IF (T.GT.200.) GO TO 703
      PCW1=2400000.
      GO TO 799
C
703  IF (T.GT.300.) GO TO 704
      PCW1=1300000.
      GO TO 799
C
704  IF (T.GT.350.) GO TO 705
      PCW1=400000.
      GO TO 799
C
705  PCW1=55000.
C
C
799  RETURN
      END
C
C
C *****
C * HEAT CAPACITY FOR CONCRETE *
C * FORMULA 1 (density 2400 kg/cu.m) *
C *****
C
      DOUBLE PRECISION FUNCTION PCC1(T)
C
      IMPLICIT REAL*8 (A-H,O-Z)
C
701  IF (T.GT.100.) GO TO 702
      PCC1=1900000.
      GO TO 799
C
702  IF (T.GT.400.) GO TO 703
      PCC1=2500000.
      GO TO 799
C
703  IF (T.GT.600.) GO TO 704
      PCC1=3500000.
      GO TO 799
C
704  PCC1=2500000.
C

```


C
 799 RETURN
 END
 C
 C

B.6. References

1. Alfawakhiri, F., Sultan, M. A., and Kodur, V. K. R., "Fire Resistance of Load Bearing Steel-Stud Walls Protected with Gypsum Board", *Proceedings of the 3rd Structural Specialty Conference of the Canadian Society for Civil Engineering*, London, ON, June 2000, pp. 114-121.
2. ASTM E119-95a, *Standard Test Methods for Fire Tests of Building Construction and Materials*, American Society for Testing and Materials, West Conshohocken, PA, June 1995.
3. Harmathy, T. Z., "A Treatise on Theoretical Fire Endurance Rating", *Fire Test Methods*, ASTM STP 301, American Society for Testing and Materials, West Conshohocken, PA, 1961, pp.10-35.
4. ISO 834, *Fire Resistance Tests - Elements of Building Construction*, International Organisation for Standardisation, Switzerland, 1992.
5. Sultan, M. A., "A Model for Predicting Heat Transfer Through Noninsulated Unloaded Steel-Stud Gypsum Board Wall Assemblies Exposed to Fire", *Fire Technology*, Vol. 32, No. 3, 1996, pp. 239-259.

Table B.1. Apparent thermal properties of Gypsum Board for Numerical Example (Type C, 12.7 mm Thick, Bulk Density 750 kg/m³).

Apparent thermal properties	Temperature range (°C)											
	<50	50-80	80-100	100-120	120-140	140-160	160-180	180-200	200-300	300-500	500-700	>700
Conductivity [W/(m°C)]	0.27	0.27	0.27	0.15	0.15	0.15	0.15	0.15	0.17	0.17	0.25	0.45
Heat capacity [MJ/(m ³ °C)]	0.49	0.70	1.4	2.8	5.6	9.1	7.0	2.8	2.8	1.4	0.49	0.35

Figure B.1. Flowchart of TRACE program.

Figure B.2. LSF Wall for Numerical Example.

Figure B.3. Simulated Temperature Histories.

Figure B.4. Simulated Heat Flux Histories.

Figure B.5. Simulated Temperature Profiles.

Appendix C

Computer Program STUD

User Manual

C.1. Introduction

For a structural assembly, the accidental situation of fully developed fire exposure can be analyzed as an ultimate limit state event that is likely to cause significant damage. Severe heating leads to the deterioration of the mechanical properties of structural materials. In addition, large thermal deformations in heated structures can cause critical stress re-distributions and unusual failure modes in structural elements. Numerical simulations help in tracing the complex interaction of thermal and structural phenomena in construction assemblies subjected to fire attack. In this context, the STUD program was developed to investigate the behaviour of cold-formed steel studs in loadbearing lightweight steel-framed (LSF) walls exposed to fire. The program has been used for retrospective simulations of six standard fire resistance tests (Alfawakhiri and Sultan 2000).

Computational techniques are becoming increasingly important as research and design tools in structural fire protection. STUD helps to produce an 'educated guess' of the expected fire resistance in situations where results of standard fire tests are not available or not applicable. STUD is a research tool that can be used to optimize future experimental programs on the fire resistance of LSF walls. Numerical results provide additional information that helps in the analysis of test data. STUD simulations can also be used for parametric studies.

C.2. Program Description

The source code for STUD is presented in Section C.5. The implemented algorithm for computing lateral deformations and extreme fibre stresses at critical sections closely follows procedures described by Alfawakhiri and Sultan (2000). The explanatory notes within the source code provide brief descriptions of the computational routines and the parameters used in the program.

STUD was successfully compiled and tested using Digital Visual Fortran Version 5.0. The executable file occupies 369 KB of storage space. The program code is compliant with standard Fortran 77, and therefore, older versions of Fortran compilers can also be used.

An input file, in ASCII text format, has to be generated and saved before program execution. At the start, the program prompts the user for the names of the input file and the output file. These names should be entered on the keyboard during program execution. The program will create an output file with the specified name and write the output data to that file. The output file is an ASCII text file, which can be easily imported into a spreadsheet application for post-processing.

The flowchart of the STUD program is shown in Figure C.1. The main program opens the input and output files, and, for every time-history step, computes load eccentricity, lateral deflections, bending moments, critical section stress ratios, and writes the results to the output file. In addition to the main program, STUD contains six subroutines: DATIN, CSECT, BOW, ELAST, GEOM and YIELD.

Subroutine DATIN reads the input file and records the input parameters to memory. These parameters describe stud dimensions, steel properties, applied vertical load, lateral deformation conditions, critical sections and time-history of temperatures at hot and cold flanges. The required format of the input file is described in the next section.

Subroutine CSECT performs the discretization of lipped-C-shaped steel stud sections. First, the overall dimensions are determined for four types of cross-sections: unreduced, effective in compression, effective in bending with hot flange compressed and effective in bending with cold flange compressed. The width of compression elements in effective stud cross-sections is determined in accordance with Clause 5.6.2 of S136-94. For perforated sections, the web is considered to consist of two unstiffened elements, one on each side of perforation, according to Clause 6.8.1 of S136-94. The effective cross-section dimensions are assumed to be insensitive to temperature, i.e. they are based on steel properties at room temperature and compressive stress equal to steel yield strength. Secondly, each of the four sections is divided to 100 finite elements. Finally, the subroutine computes the geometry parameters (area, distance to reference axis, etc.) of the finite elements for every case and records them to memory.

Subroutine BOW computes the curvature of the stud due to 'stress-free' thermal bowing, based on the difference in thermal elongation strain between the hot and cold flanges. The user can choose from three models for steel thermal elongation strain, suggested by Lie (1992), Lawson and Newman (1990) and Makelainen and Miller (1983), that are contained in the current version of the subroutine. These models are illustrated in Figure C.2. Other steel thermal strain models can be easily added to the subroutine to extend its applicability to specific steel properties or in order to conduct parametric studies on the effect of thermal elongation on fire resistance.

Subroutine ELAST calculates the temperatures of all finite elements for sections specified by subroutine CSECT, assuming a linear temperature gradient between hot and cold flanges. Based on these temperatures, the subroutine computes the temperature-dependent modulus of elasticity of steel for each finite element. The user can choose from three models for elastic modulus retention (at elevated temperatures), suggested by Gerlich (1995) and Makelainen and Miller (1983), that are implemented in the current version of the subroutine and associated functions. These models are illustrated in Figure C.3. Other steel elastic modulus models can be easily added to the subroutine to extend its applicability to specific steel properties or in order to conduct parametric studies on the effect of steel elastic modulus retention (at elevated temperatures) on fire resistance.

Subroutine GEOM computes the temperature-dependent modulus-weighted properties (area, moment of inertia, section moduli in bending) for sections specified by subroutine CSECT, based on elastic moduli of finite elements specified by subroutine ELAST.

Subroutine YIELD computes the temperature-dependent steel yield strength at the extreme fibres of hot and cold flanges. The user can choose from three models for steel yield strength at elevated temperatures, suggested by Gerlich (1995), Makelainen and Miller (1983) and BS 5950, that are contained in the current version of the subroutine and the associated functions. These models are illustrated in Figure C.4. Other steel yield strength formulas can be easily added to the subroutine to extend its applicability to specific steel properties or in order to conduct parametric studies on the effect of steel strength retention (at elevated temperatures) on fire resistance.

STUD executes structural analysis procedures for every time step (and respective hot and cold flange temperature combination) specified in the input file. At each step, the program evaluates the deflected shape of the stud and checks two user-defined (at elevations z1 and z2) critical sections for the combined action of axial load and bending moment about the strong axis. For each time step, the program writes to the output file the time ITS, the average temperature of the stud Ta, the temperature difference between the hot and cold flanges Td, the eccentricity of the applied vertical load ecc, the lateral deformation at stud mid-height Dcor, and four failure criteria:

CR1h = ratio of stress to yield strength at extreme fibre of hot flange, elevation z1;

CR1c = ratio of stress to yield strength at extreme fibre of cold flange, elevation z1;

CR2h = ratio of stress to yield strength at extreme fibre of hot flange, elevation **z2**;

CR2c = ratio of stress to yield strength at extreme fibre of cold flange, elevation **z2**.

Negative failure criteria indicate compression at respective locations, while positive failure criteria indicate tension. The section is considered to fail at the time when any absolute value of respective failure criteria exceeds unity. This time is indicative of the fire resistance of the loadbearing LSF wall (if no further load redistribution among the studs along the wall occurs).

It should be noted, that **STUD** procedures, for the evaluation of lateral deflections and load eccentricity, explicitly model phenomena, observed in full-scale fire resistance tests, that can be associated with creep and stress relaxation processes at elevated temperatures. First, the lateral deflections at any time step are not allowed to be less than in the previous time step. This technique was first introduced and used by Gerlich (1995) Secondly, at hot flange temperatures in excess of 400 °C, if lateral deflections do not increase with time, load eccentricity is reduced by 10% in every time step. These two provisions are especially useful in the structural simulations for non-insulated LSF walls exposed to fire.

It should be noted that **STUD** is a unit-sensitive program. All input for temperatures must be in °C, which are required for all models for temperature-dependent steel properties within the program. Any appropriate unit can be used for time input. A set of consistent units should be used for all other input parameters, e.g. dimensions in mm, steel modulus of elasticity and yield strength in MPa, and vertical load in N (in this case, the values for load eccentricity and lateral deflection in the output file will be in mm).

C.3. Input File Format

The order of input data by sequence of parameters needed by **STUD** is as follows:

1. Title line for problem identification (one line of up to 80 alphanumeric characters, including spaces).
2. Line, describing the geometry of lipped-C-section steel stud, consisting of seven parameters separated by commas:
Ao, Bo, Co, ts, Ro, Ap, H.
3. Line, describing steel properties, consisting of five parameters separated by commas:
E, IEt, Fy, IFyt, Iext.
4. Line, describing parameters for structural analysis, consisting of five parameters separated by commas:
EP, RCLD, NTS, z1, z2.

5. NTS lines (one line per time step), describing time-history of temperatures at hot and cold flanges, each consisting of three parameters separated by commas:
ITS, TH, TC.

Integer values should be entered for parameters, starting with letters I-N. Real values should be entered for all other parameters.

- Ao** = out to out depth of stud section.
- Bo** = out to out width of flange.
- Co** = out to out width of lip (flange stiffener).
- ts** = black metal thickness.
- Ro** = inside bend radius.
- Ap** = width of web perforation.
- H** = length of steel stud.
- E** = steel modulus of elasticity at room temperature.
- IEt** = indicator for the formulation of steel modulus of elasticity retention factor at elevated temperatures.
1 for Gerlich (1995) formula, extended to 1000 °C.
2 for Makelainen and Miller (1983) formula, for steady-state tests, extended to 1000 °C.
3 for Makelainen and Miller (1983) formula, for transient tests, extended to 1000 °C.
- Fy** = steel yield strength at room temperature.
- IFyt** = indicator for the formulation of steel yield strength retention factor at elevated temperatures.
1 for Gerlich (1995) formula, extended to 1000 °C.
2 for Makelainen and Miller (1983) formula, extended to 1000 °C.
3 for BS 5950 formulation for 0.5% strain, extended to 1000 °C.
- Iext** = indicator for the formulation of steel thermal elongation strain.
1 for Lie (1992) formula, extended to 1000 °C.
2 for Lawson and Newman (1990) formula, extended to 1000 °C.
3 for Makelainen and Miller (1983) formula, extended to 1000 °C.

P = tributary vertical load for one stud.

RCLD = reduction coefficient for lateral deflection, which depends on boundary conditions at stud ends and internal stresses caused by non-uniform heating.
 0.6 recommended for loading between parallel plates in fire resistance tests.
 > 0.6 for loading through hinges.
 < 0.6 fixed end conditions (e.g. studs imbedded in concrete footing).

NTS = number of lines (time steps), describing time-history of temperatures at hot and cold flanges.

z1 = elevation (from the lower end of stud) of the first section to be checked in the structural analysis.

z2 = elevation (from the lower end of stud) of the second section to be checked in the structural analysis.

ITS = time, or time step number (identification number for temperature combination).

TH = hot flange temperature (in °C).

TC = cold flange temperature (in °C).

C.4. Numerical Example

A standard fire resistance test (according to CAN/ULC-S101-M89) was conducted recently on loadbearing LSF wall SFF-1. The steel frame layout for the wall specimen is shown in Figure C.5. The frame consisted of ten cold-formed steel studs, 3048 mm long, spaced 406 mm o.c., with appropriate bracing, bridging and blocking that ensured lateral stability in the plane of the wall. Figure C.6 shows the cross-sectional details of the specimen. Each steel stud had a C-shaped cross-section, nominally, 92.1 mm deep by 41.3 mm wide, with 12.7-mm flange-stiffening lips and base metal thickness of 0.91 mm. The minimum specified steel yield strength was 228 MPa. Each stud had four web perforations, 38.1 mm wide, spaced 610 mm o.c. along the stud.

Temperature histories for hot and cold flanges were measured and recorded (at 1-minute intervals) during the fire-resistance test. Vertical load of 21.5 kN/m (8.7 kN/stud) was held constant for the duration of the test. The wall failed after 76 minutes of fire exposure by losing its ability to sustain the applied load. The dominant stud failure mode was the compressive failure of the cold flange near stud mid-height, usually, at the locations of the second or third (counting from the lower end of the stud) web perforations. This structural failure resulted in the overall out-of-plane buckling of the wall towards the furnace.

The use of STUD program is illustrated here by the following 77-minute structural simulation for wall SFF-1. The Steel modulus of elasticity at room temperature is assumed equal to 203000 MPa. Retention factors suggested by Gerlich (1995), for steel yield strength and modulus of elasticity at elevated temperatures, are adopted in the simulation. Lie (1992) formula is used for the evaluation of thermal strains. Critical stress analysis is performed for perforated sections at distances 609.6 and 1219.2 mm from the bottom of the wall.

The input and output files are listed in the following subsections. The simulated mid-height deflection is shown in Figure C.7 compared with the average mid-height deflection measured during the test. The output file results show that the absolute value of CR2c exceeds unity at 77 minutes, which indicates that the simulated failure occurs in the cold flange at elevation 1219.2 mm (section at the location of second web perforation) after 76 minutes of fire exposure. The negative sign of CR2c at 77 minutes indicates that this failure is compressive.

C.4.1. Input File

```
LSF WALL SFF1 (STUD RUN) Temp. Histories from Fire Test
92.1,41.3,12.7,0.91,1.82,38.1,3048.
203000.,1,228.,1,1
8700.,0.6,78,609.6,1219.2
0,22.9,23
1,22.91667,23
2,22.975,23
3,23.54167,23.1
4,25.20833,23.65
5,28.25,25.05
6,33.46667,28.08333
7,39.21667,32.26667
8,45.35833,37.3
9,51.16667,42.83334
10,56.775,48.78333
11,61.575,53.78333
12,65.02499,58.06667
13,67.79166,61.36666
14,69.44167,63.6
15,70.24167,64.83333
16,70.58333,65.55
17,70.675,65.83334
18,71.28333,66.18333
19,72.63333,67.51666
20,74.75833,69.3
21,76.40833,70.95
22,77.71666,72.4
23,79.35,73.75
24,80.71666,74.98334
25,82.10834,76.01666
```

26,83.36667,77.35
27,84.56667,78.56667
28,85.61667,79.63333
29,86.61667,80.68333
30,87.875,81.5
31,89.39166,82.26667
32,91.375,83.03333
33,93.825,83.83334
34,95.73334,84.71667
35,97.83334,85.53334
36,99.83333,86.45
37,101.7083,87.53333
38,103.6667,88.71667
39,105.9917,89.85001
40,108.6417,90.96666
41,112.5583,92.13333
42,117.7333,93.8
43,125.0083,96.38333
44,135.625,100.5167
45,148.7167,106.4833
46,164.5333,113.8833
47,182.575,123.1167
48,202.7417,134.1167
49,224.375,146.45
50,243.75,159.45
51,260.025,172.45
52,274.85,184.9333
53,290.375,196.4833
54,303.1833,207.1333
55,314.8,216.85
56,325.6667,226.1667
57,334.725,235.6333
58,344.8833,245.15
59,358.7417,255.1333
60,371.2167,265.7667
61,384.7833,276.8167
62,399.7584,288.5833
63,414.6667,300.7833
64,431.8333,313.0833
65,444.6083,326.2833
66,456.35,339.8333
67,467.0083,353.0333
68,475.9167,365.4833
69,484.4333,377.3666
70,494.275,389.8167
71,512.325,403.3
72,513.5417,417.8167
73,518.1417,428.0667
74,522.925,440.9167
75,528.1583,452.05
76,532.8834,463.9333
77,535.2083,485.4833

C.4.2. Output File

1

```

LSF WALL SFF1 (STUD RUN) Temp. Histories from Fire Test
ITS      Ta      Td      ecc      Dcor      CR1h      CR1c      CR2h      CR2c
0        22.9     0.0     0.0     0.0     -0.341    -0.341    -0.341    -0.341
1        23.0     0.0     0.0     0.0     -0.341    -0.341    -0.341    -0.341
2        23.0     0.0     0.0     0.0     -0.341    -0.341    -0.341    -0.341
3        23.3     0.4     0.1     0.0     -0.341    -0.340    -0.341    -0.340
4        24.4     1.6     0.5     0.2     -0.344    -0.338    -0.343    -0.339
5        26.6     3.2     0.9     0.4     -0.347    -0.336    -0.346    -0.337
6        30.8     5.4     1.6     0.6     -0.352    -0.333    -0.350    -0.334
7        35.7     7.0     2.0     0.8     -0.355    -0.331    -0.353    -0.332
8        41.3     8.1     2.3     0.9     -0.358    -0.329    -0.356    -0.332
9        47.0     8.3     2.4     0.9     -0.359    -0.329    -0.357    -0.332
10       52.8     8.0     2.3     0.9     -0.359    -0.331    -0.356    -0.333
11       57.7     7.8     2.3     0.9     -0.359    -0.332    -0.356    -0.334
12       61.5     7.0     2.0     0.9     -0.357    -0.334    -0.354    -0.336
13       64.6     6.4     1.9     0.9     -0.356    -0.335    -0.353    -0.338
14       66.5     5.8     1.7     0.9     -0.355    -0.337    -0.352    -0.339
15       67.5     5.4     1.6     0.9     -0.354    -0.338    -0.351    -0.340
16       68.1     5.0     1.5     0.9     -0.353    -0.339    -0.350    -0.341
17       68.3     4.8     1.4     0.9     -0.352    -0.339    -0.349    -0.341
18       68.7     5.1     1.5     0.9     -0.353    -0.338    -0.350    -0.341
19       70.1     5.1     1.5     0.9     -0.353    -0.339    -0.350    -0.341
20       72.0     5.5     1.6     0.9     -0.354    -0.338    -0.351    -0.340
21       73.7     5.5     1.6     0.9     -0.354    -0.338    -0.351    -0.340
22       75.1     5.3     1.5     0.9     -0.354    -0.338    -0.351    -0.341
23       76.5     5.6     1.6     0.9     -0.355    -0.338    -0.352    -0.340
24       77.8     5.7     1.7     0.9     -0.355    -0.338    -0.352    -0.340
25       79.1     6.1     1.8     0.9     -0.356    -0.337    -0.353    -0.339
26       80.4     6.0     1.7     0.9     -0.356    -0.337    -0.353    -0.340
27       81.6     6.0     1.7     0.9     -0.356    -0.337    -0.353    -0.340
28       82.6     6.0     1.7     0.9     -0.356    -0.338    -0.353    -0.340
29       83.7     5.9     1.7     0.9     -0.356    -0.338    -0.353    -0.340
30       84.7     6.4     1.8     0.9     -0.357    -0.337    -0.355    -0.339
31       85.8     7.1     2.1     0.9     -0.359    -0.335    -0.357    -0.338
32       87.2     8.3     2.4     0.9     -0.362    -0.333    -0.360    -0.335
33       88.8     10.0    2.9     1.1     -0.366    -0.330    -0.362    -0.333
34       90.2     11.0    3.2     1.3     -0.368    -0.329    -0.364    -0.332
35       91.7     12.3    3.6     1.4     -0.370    -0.327    -0.366    -0.330
36       93.1     13.4    3.9     1.5     -0.372    -0.325    -0.368    -0.329
37       94.6     14.2    4.1     1.6     -0.374    -0.324    -0.369    -0.328
38       96.2     15.0    4.3     1.7     -0.376    -0.323    -0.371    -0.327
39       97.9     16.1    4.7     1.8     -0.378    -0.321    -0.373    -0.326
40       99.8     17.7    5.1     2.0     -0.381    -0.319    -0.375    -0.324
41      102.3     20.4    5.9     2.3     -0.387    -0.314    -0.380    -0.320
42      105.8     23.9    6.9     2.7     -0.394    -0.309    -0.386    -0.316
43      110.7     28.6    8.3     3.3     -0.403    -0.302    -0.393    -0.310
44      118.1     35.1   10.1     4.0     -0.416    -0.292    -0.404    -0.302
45      127.6     42.2   12.2     4.9     -0.431    -0.281    -0.416    -0.294
46      139.2     50.6   14.6     5.9     -0.448    -0.269    -0.431    -0.284
47      152.8     59.5   17.0     7.0     -0.468    -0.257    -0.447    -0.275
48      168.4     68.6   19.6     8.1     -0.489    -0.246    -0.464    -0.266

```

49	185.4	77.9	22.1	9.3	-0.512	-0.235	-0.483	-0.259
50	201.6	84.3	23.7	10.1	-0.530	-0.229	-0.498	-0.255
51	216.2	87.6	24.4	10.6	-0.542	-0.229	-0.509	-0.256
52	229.9	89.9	24.8	10.9	-0.554	-0.230	-0.518	-0.259
53	243.4	93.9	25.7	11.5	-0.569	-0.230	-0.531	-0.260
54	255.2	96.0	26.0	11.8	-0.581	-0.232	-0.541	-0.264
55	265.8	98.0	26.3	12.2	-0.592	-0.235	-0.550	-0.268
56	275.9	99.5	26.5	12.4	-0.603	-0.238	-0.559	-0.272
57	285.2	99.1	26.1	12.4	-0.610	-0.244	-0.565	-0.279
58	295.0	99.7	26.0	12.6	-0.620	-0.250	-0.573	-0.285
59	306.9	103.6	26.6	13.2	-0.640	-0.253	-0.590	-0.290
60	318.5	105.4	26.7	13.6	-0.657	-0.260	-0.604	-0.299
61	330.8	108.0	26.9	14.0	-0.678	-0.267	-0.621	-0.308
62	344.2	111.2	27.2	14.6	-0.704	-0.276	-0.641	-0.320
63	357.7	113.9	27.2	15.1	-0.731	-0.288	-0.663	-0.334
64	372.5	118.8	27.6	16.0	-0.770	-0.300	-0.693	-0.350
65	385.4	118.3	26.9	16.1	-0.793	-0.319	-0.711	-0.371
66	398.1	116.5	23.3	16.1	-0.771	-0.367	-0.686	-0.420
67	410.0	114.0	19.8	16.1	-0.747	-0.417	-0.657	-0.472
68	420.7	110.4	16.4	16.1	-0.718	-0.468	-0.624	-0.525
69	430.9	107.1	13.3	16.1	-0.691	-0.518	-0.599	-0.580
70	442.0	104.5	10.5	16.1	-0.671	-0.571	-0.582	-0.640
71	457.8	109.0	12.6	16.3	-0.770	-0.580	-0.665	-0.650
72	465.7	95.7	9.1	16.3	-0.716	-0.648	-0.616	-0.726
73	473.1	90.1	6.7	16.3	-0.694	-0.707	-0.592	-0.787
74	481.9	82.0	4.5	16.3	-0.677	-0.773	-0.571	-0.858
75	490.1	76.1	2.7	16.3	-0.668	-0.836	-0.559	-0.924
76	498.4	69.0	1.2	16.3	-0.663	-0.902	-0.551	-0.995
77	510.3	49.7	0.0	16.3	-0.674	-1.001	-0.560	-1.104

C.5. FORTRAN source code for STUD program.

```

C *****
C * Stud - Simulation of structural behavior of loadbearing LSF walls in *
C * standard fire resistance tests. *
C * (Simulation of structural behavior of lipped-C-section studs *
C * subjected to vertical load and severe heating) *
C * *
C * The program algorithm closely follows procedures described in "Fire *
C * Resistance of Loadbearing LSF Assemblies", by F. Alfawakhiri and *
C * M.A.Sutan, Proceedings of the 15th International Specialty Conference *
C * on Cold-Formed Steel Structures, St. Louis, MO, October 2000. *
C * Assumptions: *
C * * LSF wall is modelled by a single stud with initial imperfection *
C * (due to thermal bowing) subjected to eccentric tributary load. *
C * * Gypsum board does not carry any loads. *
C * * Flexural-torsional and weak axis buckling failure modes are *
C * prevented by adequate lateral restraints. *
C * * Steel stress-strain relationships at elevated temperatures are *
C * linear up to the yield strength. *
C * * The stud is hinged at the ends (the eccentricity of the vertical *
C * tributary load in part simulates the rotational end restraint *
C * conditions). *
C * * There is no temperature variation in the vertical direction *
C * along the stud. However, the temperature varies across the stud *
C * section from the hot flange to the cold flange. *
C * * The initial imperfection (thermal bowing) is stress-free, i.e. *

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C      *      a linear gradient of thermal elongation strain across the stud      *
C      *      section is assumed (the eccentricity of the vertical tributary      *
C      *      load in part simulates/approximates the state of internal stress      *
C      *      caused by non-linear strain gradients). The temperature gradient      *
C      *      across the section is also approximated as linear.                  *
C      *
C      *      At each time step, this program evaluates the deflected shape of the      *
C      *      stud, and checks two (user-defined) critical sections for the combined      *
C      *      action of axial load and bending moment (about strong axis).          *
C      *      The final output for every time step are four failure criteria (2 per      *
C      *      section), which are ratios of extreme fibre stresses to the respective      *
C      *      yield strength at the temperature associated with that location).        *
C      *      The section is considered to fail at the time when any of its failure      *
C      *      criteria exceeds unity. This time is indicative of the fire resistance      *
C      *      of the loadbearing LSF wall (if no further load redistribution between      *
C      *      studs along the wall occurs).
C      *
C      *      The program applies to lipped-C-section studs only. Routines can be      *
C      *      added for other types of sections, if their structural behavior, when      *
C      *      subjected to severe heating, is known to be similar.
C      *
C      *      Width of compression elements in effective stud cross-sections is      *
C      *      determined in accordance with Clause 5.6.2 of S136-94 to account for      *
C      *      local buckling effects. For perforated sections, the web is considered      *
C      *      to consist of 2 unstiffened elements, one on each side of perforation,      *
C      *      according to Clause 6.8.1 of S136-94. Effective cross-section          *
C      *      dimensions are assumed to be insensitive to temperature (i.e. based on      *
C      *      steel properties at room temperature, and compressive stress  $f=F_y$ ).      *
C      *      See Subroutine CSECT.
C      *
C      *      Modulus-weighted (temperature-dependent) section properties are      *
C      *      computed at every time step for 4 types of sections: unreduced,          *
C      *      in compression, in bending with hot flange compressed, in bending with      *
C      *      cold flange compressed. See Subroutine GEOM.
C      *
C      *      Three models for steel thermal elongation strain implemented (see      *
C      *      Subroutine BOW). Three models for steel modulus of elasticity            *
C      *      retention factor implemented (see Subroutine ELST and associated          *
C      *      functions). Three models for steel yield strength retention factor        *
C      *      implemented (see Subroutine YIELD and associated functions). Other        *
C      *      models, associated with steel properties at elevated temperatures,        *
C      *      can be added to these subroutines (if known from experiments, or for      *
C      *      parametric studies).
C      *
C      *      Creep/Stress Relaxation procedure implemented. Lateral deflections      *
C      *      cannot be less than in the previous time step. At hot flange            *
C      *      temperatures > than 400 deg.C, if deflections do not increase with      *
C      *      time, load eccentricity is reduced by 10% in every time step.
C      *
C      *
C      *      BY FARID ALFAWAKHIRI - LAST REVISED ON August 24, 2000
C      *      *****
C
C      IMPLICIT REAL*8 (A-H,O-Z)
C      CHARACTER INPUT*80, OUTPUT*80
C      COMMON/SET1/ ITS(1000), TH(1000), TC(1000)
C      COMMON/SET2/ AE1(100), Io1(100), YE1(100), E1(100)
C      COMMON/SET3/ AE2(100), Io2(100), YE2(100), E2(100)
C      COMMON/SET4/ AE3(100), Io3(100), YE3(100), E3(100)
C      COMMON/SET5/ AE4(100), Io4(100), YE4(100), E4(100)
C
C      Specify input and output files
C
C      WRITE (*,1000)
1000 FORMAT (2X,'Program STUD - fire resistance'
1         ' of loadbearing LSF walls'/)
C      WRITE (*,1001)

```



```

1001 FORMAT (2X,'ENTER THE NAME OF THE INPUT FILE:',$)
      READ (*,1003) INPUT
      WRITE (*,1002)
1002 FORMAT (2X,'ENTER THE NAME OF THE OUTPUT FILE:',$)
      READ (*,1003) OUTPUT
1003 FORMAT (1A80)
C
C      Open input and output files
C
      CLOSE (9)
      CLOSE (7)
      OPEN (9,FILE=INPUT,STATUS='OLD')
      OPEN (7,FILE=OUTPUT,STATUS='NEW')
C
C      Read the input file
C
      CALL DATIN (Ao, Bo, Co, ts, Ro, Ap, H,
1          E, IEt, Fy, IFyt, Iext, P, RCLD, NTS, z1, z2)
C
C      Discretize stud section and reduced sections (in compression and bending)
C      Currently each section is divided to 100 elements
C
      CALL CSECT (Ao, Bo, Co, ts, Ro, Ap, Fy, E)
C
C      Set up initial parameters
C      Calculate section geometry properties at room temperatures
C
      EH=1.
      EC=1.
      DO 11 I=1,100
      E1(I)=1.
      E2(I)=1.
      E3(I)=1.
      E4(I)=1.
11 CONTINUE
C
      CALL GEOM (Ao,CG1,CG3,CG4,WI1,A2,S3c,S3t,S4c,S4t)
      BI=WI1
      ITSo=-1
      Ta=0.0
      Td=0.0
      Fyh=Fy
      Fyc=Fy
      CHCK=1.
      BETA2=BI*E/P
      BETA=DSQRT(1/BETA2)
      U=0.5*BETA*H
      ecc=0.
      ecc1=0.
      ecc2=0.
      Dthc=0.
      Dcor=0.
      D1c=0.
      D2c=0.
      CR1h=-P/A2/Fy
      CR1c=CR1h
      CR2h=CR1h
      CR2c=CR1h
C
      WRITE (7,1005) ITSo,Ta,Td,CG1,CG3,CG4,BI,A2,S3c,S3t,S4c,S4t,
1          EH,EC,Fyh,Fyc,CHCK,U,ecc,ecc1,ecc2,
2          Dthc,Dcor,D1c,D2c,CR1h,CR1c,CR2h,CR2c
C
      RLX=0.
      DMAX1=0.
      DMAX2=0.
      DMAX3=0.
      DMAX4=0.

```

```

WRITE (7, 1008)
1008 FORMAT (3X, 'ITS', 6X, 'Ta', 6X, 'Td', 4X, 'ecc', 3X, 'Dcor',
1         4X, 'CR1h', 4X, 'CR1c', 4X, 'CR2h', 4X, 'CR2c')
C
C   Do repeated operations at every time (temperature combination) step
C
C   DO 101 IT=1,NTS
C
C   Compute average temperature Ta of the stud, and the temperature difference
C   Td between the hot flange and the cold flange
C
C   Tmax=TH(IT)
C   Tmin=TC(IT)
C   Ta=(Tmax+Tmin)/2.
C   Td=Tmax-Tmin
C   IF (Td. LT. 0.) Td=0.
C
C   Compute the thermal expansion stains at extreme hot and cold fibres,
C   then the assumed stress-free thermal bowing curvature FI, and the
C   mid-height initial imperfection (due to thermal bowing) Dth
C   Dthc = corrected Dth, which is not less than Dth in previous time step
C
C   CALL BOW (Ao,Tmax,Tmin,Iext,FI)
C   Dth=FI*H*H/8.
C   Dthc=Dth
C   IF (Dthc. LT. DMAX1) Dthc=DMAX1
C   IF (Dthc. GE. DMAX1) DMAX1=Dthc
C
C   Compute modulus of elasticity retention factors for each discretized
C   section element and section extreme fibres
C   GRAD = temperature gradient (linear) across steel section, deg.C/mm
C   EH   = modulus of elasticity retention factor at extreme hot fibre
C   EC   = modulus of elasticity retention factor at extreme cold fibre
C   E1, E2, E3, E4 are modulus retention factors for section elements
C
C   GRAD=Td/Ao
C   CALL ELAST (IET,Tmax,Tmin,GRAD,EH,EC)
C
C   Compute modulus weighted section properties
C
C   CALL GEOM (Ao,CG1,CG3,CG4,WI1,A2,S3c,S3t,S4c,S4t)
C   Ea=(1.-3.E-4*Ta+3.7E-7*Ta**2-6.1E-9*Ta**3+5.4E-12*Ta**4)
C   CHCK=WI1/(Ea*BI)
C
C   Compute the temperature dependent yield strength in the extreme fibres
C   of hot and cold flanges
C
C   CALL YIELD (Fy,IFyt,Tmax,Tmin,Fyh,Fyc)
C
C   Compute the Beta and u parameters (from the secant formula for an
C   eccentrically loaded column)
C
C   BETA2=WI1*E/P
C   BETA=DSQRT(1./BETA2)
C   U=0.5*BETA*H
C
C   Compute the total lateral deformation D at stud mid-height and
C   total lateral deformations Dz1 and Dz2 at user-specified elevations
C   z1 and z2 of critical section to check.
C   When Td decreases with time, D, Dz1 and Dz2 are forced not to decrease.
C   At TH > 400 deg.C, if D doesn't increase with time, stress relaxation
C   occurs. This is modelled by applying 10% reduction to load eccentricity
C   ecc at every consequent time step (RLX = relaxation factor).
C   Dcor = corrected D, which is not less than D in previous time step
C   D1c = corrected Dz1, which is not less than Dz1 in previous time step
C   D2c = corrected Dz2, which is not less than Dz2 in previous time step
C   ecc = load eccentricity
C

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      D=RCLD*FI*BETA2*(1./COS(U)-1.)
      Dcor=D
      IF (Dcor. GE. DMAX2) Go to 171
      Dcor=DMAX2
      IF (Tmax.GT.400.) RLX=RLX+1.
      IF (RLX.GT.10.) RLX=10.
      Go to 172
171  DMAX2=Dcor
      RLX=RLX-1.
      IF (RLX.LT.0.) RLX=0.
172  ecc=(1.-0.1*RLX)*(1.-RCLD)*FI*BETA2
C
      U1=BETA*z1
      Dz1=RCLD*FI*BETA2*(TAN(U)*SIN(U1)+COS(U1)-1.)
      D1c=Dz1
      IF (D1c. LT. DMAX3) D1c=DMAX3
      IF (D1c. GE. DMAX3) DMAX3=D1c
C
      U2=BETA*z2
      Dz2=RCLD*FI*BETA2*(TAN(U)*SIN(U2)+COS(U2)-1.)
      D2c=Dz2
      IF (D2c. LT. DMAX4) D2c=DMAX4
      IF (D2c. GE. DMAX4) DMAX4=D2c
C
C      Compute bending moments at user-specified critical sections
C
      ecc1=D1c-ecc
      ecc2=D2c-ecc
      BM1=P*ecc1
      BM2=P*ecc2
C
C      Compute stresses at extreme fibres Flc, Flt, F2c, F2t
C      and the corresponding critical stress ratios CR1h, CR1c, CR2h, CR2c
C      Flc = stress at extreme compression fibre, at elevation z1
C      Flt = stress at extreme tension fibre, at elevation z1
C      F2c = stress at extreme compression fibre, at elevation z2
C      F2t = stress at extreme tension fibre, at elevation z2
C      CR1h = critical ratio, hot flange, elevation z1
C      CR1c = critical ratio, cold flange, elevation z1
C      CR2h = critical ratio, hot flange, elevation z2
C      CR2c = critical ratio, cold flange, elevation z2
C
      IF (BM1. LT. 0.) GO TO 112
      Flc=EC*(-P/A2-BM1/S4c)
      Flt=EH*(-P/A2+BM1/S4t)
      CR1h=Flt/Fyh
      CR1c=Flc/Fyc
      GO TO 111
112 Flc=EH*(-P/A2+BM1/S3c)
      Flt=EC*(-P/A2-BM1/S3t)
      CR1h=Flc/Fyh
      CR1c=Flt/Fyc
111 CONTINUE
C
      IF (BM2. LT. 0.) GO TO 122
      F2c=EC*(-P/A2-BM2/S4c)
      F2t=EH*(-P/A2+BM2/S4t)
      CR2h=F2t/Fyh
      CR2c=F2c/Fyc
      GO TO 121
122 F2c=EH*(-P/A2+BM2/S3c)
      F2t=EC*(-P/A2-BM2/S3t)
      CR2h=F2c/Fyh
      CR2c=F2t/Fyc
121 CONTINUE
C
C      Write the results of the time step to the output file
C

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```

C      WRITE (7,1005) ITS(IT),Ta,Td,CG1,CG3,CG4,WI1,A2,S3c,S3t,S4c,S4t,
C      1      EH,EC,Fyh,Fyc,CHCK,U,ecc,ecc1,ecc2,
C      2      Dthc,Dcor,Dlc,D2c,CR1h,CR1c,CR2h,CR2c
C 1005 FORMAT (2X,I4,2F8.1,3F7.1,6E14.5,2F8.3,2F8.1,2F8.3,7F7.1,4F8.3)
C
C      WRITE (7, 1007) ITS(IT),Ta,Td,ecc,Dcor,CR1h,CR1c,CR2h,CR2c
C 1007 FORMAT (2X,I4,2F8.1,2F7.1,4F8.3)
C
C 101 CONTINUE
C
C      STOP
C      END
C
C
C      *****
C      * DATIN *
C      * READS THE INPUT FILE
C      *****
C
C      SUBROUTINE DATIN (Ao, Bo, Co, ts, Ro, Ap, H,
C 1      E, IEt, Fy, IFyt, Iext, P, RCLD, NTS, z1, z2)
C
C      IMPLICIT REAL*8 (A-H,O-Z)
C      DIMENSION TITLE(20)
C      COMMON/SET1/ ITS(1000), TH(1000), TC(1000)
C
C      PROBLEM IDENTIFICATION
C
C      READ (9,2001) TITLE
C 2001 FORMAT (20A4)
C      WRITE (7,2002) TITLE
C 2002 FORMAT (1H1/,2X,20A4)
C
C      READ geometry parameters (for lipped-C-section)
C      Ao = out to out depth of stud section
C      Bo = out to out width of flange
C      Co = out to out width of lip stiffener
C      ts = black metal thickness
C      Ro = inside bend radius (not more than 4ts)
C      Ap = width of web perforation
C      H = effective length of steel stud (LSF wall height)
C
C      READ (9,*) Ao, Bo, Co, ts, Ro, Ap, H
C
C      READ steel sheet properties
C      E = modulus of elasticity of steel at room temperature
C      IEt = indicator for the formulation of the modulus of elasticity
C      retention factor at elevated temperatures
C      1 for Gerlich (1995) formula, extended to 1000 degrees C
C      2 for Makelainen and Miller (1983) formula for steady-state tests
C      3 for Makelainen and Miller (1983) formula for transient tests
C      Fy = yield strength of steel
C      IFyt= indicator for the formulation of the yield strength retention
C      factor at elevated temperatures
C      1 for Gerlich (1995) formula, extended to 1000 degrees C
C      2 for Makelainen and Miller (1983) formula, extended to 1000 deg. C
C      3 for BS 5950: Part 8 formula, extended to 1000 deg. C
C      Iext= indicator for the formulation of steel thermal elongation strain
C      1 for Lie (1992) formula, extended to 1000 degrees C
C      2 for Lawson and Newman (1990) formula, extended to 1000 degrees C
C      3 for Makelainen and Miller (1983) formula, extended to 1000 degrees C
C
C      READ (9,*) E, IEt, Fy, IFyt, Iext
C
C      P = tributary vertical load for one stud
C      RCLD= reduction coefficient for lateral deflection formula, which depends
C      on boundary conditions at stud ends
C      0.6 recommended for loading between two parallel plates

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C          >0.6 for loading through hinges
C          <0.6 for fixed end conditions (e.g. imbedded in concrete footing)
C      NTS = number of time steps (hot/cold flange temperature combinations),
C          current dimension of the program limits NTS to 1000
C      z1 = elevation (from bottom of wall) of first critical section to check
C      z2 = elevation (from bottom of wall) of second critical section to check
C
C
C      READ (9,*) P, RCLD, NTS, z1, z2
C
C      READ for every time step:
C      ITS = time, or time step number (combination identification number)
C      TH = hot flange temperature
C      TC = cold flange temperature
C      (Note: currently number of ITS, TH and TC is limited by 1000)
C      and close the input file
C
C      DO 201 I=1,NTS
C      READ (9,*) ITS(I), TH(I), TC(I)
201 CONTINUE
C
C      CLOSE (9)
C
C
C      RETURN
C      END
C
C
C      *****
C      * CSECT *
C      * DISCRETIZES LIPPED-C-SECTION *
C      * (SINGLY SYMMETRIC) *
C      *****
C
C      SUBROUTINE CSECT (Ao, Bo, Co, ts, Ro, Ap, Fy, E)
C
C      IMPLICIT REAL*8 (A-H,O-Z)
C      COMMON/SET2/ AE1(100), Io1(100), YE1(100)
C      COMMON/SET3/ AE2(100), Io2(100), YE2(100)
C      COMMON/SET4/ AE3(100), Io3(100), YE3(100)
C      COMMON/SET5/ AE4(100), Io4(100), YE4(100)
C
C      Compute geometry of flat elements
C      r = mid-thickness bend radius
C      A = web flat width
C      B = flange flat width
C      C = lip flat width
C
C      r=Ro+0.5*ts
C      A=Ao-ts-2.*r
C      B=Bo-ts-2.*r
C      C=Co-ts-Ro
C
C      Discretize the unreduced unperforated section to 100 elements
C      Elements 1 and 100 are flanges
C      Elements 2 and 99 are bent parts of section
C      Elements 3-10 and 91-98 are lips
C      Elements 11-50 and 51-90 are web
C      AE1 = area of discretization element
C      Io1 = moment of inertia of element about an axis, parallel to the axis
C          of symmetry of the section, passing through the centroid of element
C      YE1 = distance from centroid of element to the outside face of cold flange
C
C      AE1(1)=B*ts
C      Io1(1)=AE1(1)*ts*ts/12.
C      YE1(1)=0.5*ts
C
C      AE1(2)=3.1416*ts*r

```

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      Io1(2)=0.29845*r*r*r*ts
      YE1(2)=0.5*ts+0.3634*r
C
      AE1(3)=C*ts/8.
      Io1(3)=AE1(3)*C*C/768.
      YE1(3)=0.5*ts+r+C/16.
      DO 301 I=4,10
      AE1(I)=AE1(3)
      Io1(I)=Io1(3)
      YE1(I)=YE1(I-1)+C/8.
301 CONTINUE
C
      AE1(11)=A*ts/80.
      Io1(11)=AE1(11)*A*A/76800.
      YE1(11)=0.5*ts+r+A/160.
      DO 302 I=12,50
      AE1(I)=AE1(11)
      Io1(I)=Io1(11)
      YE1(I)=YE1(I-1)+A/80.
302 CONTINUE
C
      DO 303 I=51,100
      AE1(I)=AE1(101-I)
      Io1(I)=Io1(101-I)
      YE1(I)=Ao-YE1(101-I)
303 CONTINUE
C
C      Calculate the reduced width of lip stiffener (for f=Fy) according to
C      clause 5.6.2.7 of S136-94
C      Cef = effective width of lip stiffener
C      WB = flat width ratio
C      LIM1 and LIM2 = limiting flat width ratios
C
      WB=C/ts
      LIM1=0.644*DSQRT(0.43*E/Fy)
      IF (WB. GT. LIM1) GO TO 312
      Cef=C
      GO TO 311
312 Cef=ts*1.475*LIM1*(1.-0.323*LIM1/WB)
311 CONTINUE
C
C      Calculate the reduced width of flange in compression (for f=Fy) according
C      to clause 5.6.2.3 of S136-94
C      Bef = effective width of flange
C      Dummy parameters DUM1, DUM2, DUM3, ks
C
      LIM2=0.644*DSQRT(4.0*E/Fy)
      WB=B/ts
      DUM1=Co/B
      IF (WB. GT. LIM1) GO TO 322
      Bef=B
      GO TO 320
C
322 IF (WB. GT. LIM2) GO TO 327
      DUM2=((C/(ts*(WB/LIM2-0.327)))*3.)/4788.
      IF (DUM2. LT. 1.) Cef=Cef*DUM2
      IF (DUM1. GT. 0.25) GO TO 323
      IF (DUM2. GE. 1.) ks=4.
      IF (DUM2. LT. 1.) ks=3.57*DSQRT(DUM2)+0.43
      GO TO 321
323 IF (DUM2. GE. 1.) ks=5.25-5.*DUM1
      IF (DUM2. LT. 1.) ks=(4.82-5.*DUM1)*DSQRT(DUM2)+0.43
      GO TO 321
C
327 DUM2=((C/(ts)*3.)/12./(115.*WB/LIM2+5.))
      IF (DUM2. LT. 1.) Cef=Cef*DUM2
      IF (DUM1. GT. 0.25) GO TO 328
      IF (DUM2. GE. 1.) ks=4.

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      IF (DUM2. LT. 1.) ks=3.57*(DUM2**0.333)+0.43
      GO TO 321
328 IF (DUM2. GE. 1.) ks=5.25-5.*DUM1
      IF (DUM2. LT. 1.) ks=(4.82-5.*DUM1)*(DUM2**0.333)+0.43
C
321 CONTINUE
      DUM3=DSQRT(ks*E/Fy)
      Bef=ts*0.95*DUM3*(1.-0.208*DUM3/WB)
      IF (Bef.GT.B) Bef=B
320 CONTINUE
C
C      Calculate the reduced width of web (for f=Fy) according to
C      clause 5.6.2.2 of S136-94
C      Aef = effective width of web
C      Aef2= effective width of half web
C
      WB=A/ts
      IF (WB. LE. LIM2) Aef=A
      IF (WB. GT. LIM2) Aef=1.475*LIM2*(1.-0.323*LIM2/WB)
      Aef2=Aef/2.
C
C      If the critical sections to check are perforated sections (Ap>0)
C      the web is considered to consist of 2 unstiffened elements, according to
C      clause 6.8.1 of S136-94, with the width of each unstiffened element
C      determined according to clause 5.6.2.7 of S136-94
C
      IF (Ap. LE. 0.) GO TO 331
      DUM1=0.5*(A-Ap)
      WB=DUM1/ts
      IF (WB. LE. LIM1) DUM2=DUM1
      IF (WB. GT. LIM1) DUM2=ts*1.475*LIM1*(1.-0.323*LIM1/WB)
      IF (DUM2. LT. Aef2) Aef2=DUM2
331 CONTINUE
C
C      Discretize the reduced section FOR COMPRESSION to 100 elements
C      Elements 1 and 100 are flanges
C      Elements 2 and 99 are bended parts of section
C      Elements 3-10 and 91-98 are lips
C      Elements 11-50 and 51-90 are web
C      AE2 = area of discretization element
C      Io2 = moment of inertia of element about an axis, parallel to the axis
C      of symmetry of the section, passing through the centroid of element
C      YE2 = distance from centroid of element to the outside face of cold flange
C
      AE2(1)=Bef*ts
      Io2(1)=AE2(1)*ts*ts/12.
      YE2(1)=YE1(1)
C
      AE2(2)=AE1(2)
      Io2(2)=Io1(2)
      YE2(2)=YE1(2)
C
      AE2(3)=Cef*ts/8.
      Io2(3)=AE2(3)*Cef*Cef/768.
      YE2(3)=0.5*ts+r+Cef/16.
      DO 341 I=4,10
      AE2(I)=AE2(3)
      Io2(I)=Io2(3)
      YE2(I)=YE2(I-1)+Cef/8.
341 CONTINUE
C
      AE2(11)=Aef2*ts/40.
      Io2(11)=AE2(11)*Aef2*Aef2/19200.
      YE2(11)=0.5*ts+r+Aef2/80.
      DO 342 I=12,50
      AE2(I)=AE2(11)
      Io2(I)=Io2(11)
      YE2(I)=YE2(I-1)+Aef2/40.

```

```

342 CONTINUE
C
    DO 343 I=51,100
        AE2(I)=AE2(101-I)
        Io2(I)=Io2(101-I)
        YE2(I)=Ao-YE2(101-I)
343 CONTINUE
C
    Discretize the reduced section FOR BENDING (HOT FLANGE COMPRESSED)
C    Elements 1 and 100 are flanges
C    Elements 2 and 99 are bent parts of section
C    Elements 3-10 and 91-98 are lips
C    Elements 11-50 and 51-90 are web
C    AE3 = area of discretization element
C    Io3 = moment of inertia of element about an axis, parallel to the axis
C          of symmetry of the section, passing through the centroid of element
C    YE3 = distance from centroid of element to the outside face of cold flange
C
    DO 351 I=1,10
        AE3(I)=AE1(I)
        Io3(I)=Io1(I)
        YE3(I)=YE1(I)
351 CONTINUE
C
    IF (Ap. LE. 0.) GO TO 354
    Aef2=0.5*(A-Ap)
    AE3(11)=Aef2*ts/40.
    Io3(11)=AE3(11)*Aef2*Aef2/19200.
    YE3(11)=0.5*ts+r+Aef2/80.
    DO 352 I=12,50
        AE3(I)=AE3(11)
        Io3(I)=Io3(11)
        YE3(I)=YE3(I-1)+Aef2/40.
352 CONTINUE
C
    DO 353 I=51,90
        AE3(I)=AE2(I)
        Io3(I)=Io2(I)
        YE3(I)=YE2(I)
353 CONTINUE
    GO TO 357
C
354 DO 355 I=11,90
    AE3(I)=AE1(I)
    Io3(I)=Io1(I)
    YE3(I)=YE1(I)
355 CONTINUE
C
357 DO 358 I=91,100
    AE3(I)=AE2(I)
    Io3(I)=Io2(I)
    YE3(I)=YE2(I)
358 CONTINUE

C
    Discretize the reduced section FOR BENDING (COLD FLANGE COMPRESSED)
C    Elements 1 and 100 are flanges
C    Elements 2 and 99 are bent parts of section
C    Elements 3-10 and 91-98 are lips
C    Elements 11-50 and 51-90 are web
C    AE4 = area of discretization element
C    Io4 = moment of inertia of element about an axis, parallel to the axis
C          of symmetry of the section, passing through the centroid of element
C    YE4 = distance from centroid of element to the outside face of cold flange
C
    DO 371 I=1,100
        AE4(I)=AE3(101-I)
        Io4(I)=Io3(101-I)

```



```

      YE4(I)=Ao-YE3(101-I)
371 CONTINUE
C
C
      RETURN
      END
C
C
C
C *****
C * BOW *
C * COMPUTES CURVATURE DUE TO
C * THERMAL BOWING
C *****
C
      SUBROUTINE BOW (Ao,TH,TC,Iext,FI)
C
      IMPLICIT REAL*8 (A-H,O-Z)
C
      Compute thermal strains in hot and cold flanges, depending on the adopted
      model for the formulation of steel thermal elongation strain
      TH = hot flange temperature, degrees C
      TC = cold flange temperature, degrees C
      STH = thermal elongation strain in hot flange
      STC = thermal elongation strain in cold flange
      Iext = 1 for Lie (1992) formula
           = 2 for Lawson and Newman (1990) formula
           = 3 for Makelainen and Miller (1983) formula
C
      401 IF (Iext. NE. 1) GO TO 402
          STH=0.000000002*TH*TH+0.000012*TH-0.0002408
          STC=0.000000002*TC*TC+0.000012*TC-0.0002408
          GO TO 499
C
      402 IF (Iext. NE. 2) GO TO 403
          STH=0.000000004*TH*TH+0.000012*TH-0.0002416
          STC=0.000000004*TC*TC+0.000012*TC-0.0002416
          GO TO 499
C
      403 IF (Iext. NE. 3) GO TO 498
          IF (TH. LE. 200.) STH=0.00000472*TH-0.0000944
          IF (TH. GT. 200.) STH=0.000000005*TH*TH+0.000008*TH-0.000095
          IF (TH. GT. 500.) STH=0.000000020*TH*TH-0.000007*TH+0.0028
          IF (TH. LE. 200.) STC=0.00000472*TC-0.0000944
          IF (TC. GT. 200.) STC=0.000000005*TC*TC+0.000008*TC-0.000095
          IF (TC. GT. 500.) STC=0.000000020*TC*TC-0.000007*TC+0.0028
          GO TO 499
C
      498 WRITE (*,4001) Iext
      4001 FORMAT (5X,'UNKNOWN MODEL',I3,2X,'FOR THERMAL ELONGATION')
          STOP
C
      499 FI=(STH-STC)/Ao
          IF (FI. LT. 0.) FI=0.
C
C
      RETURN
      END
C
C
C
C *****
C * ELAST *
C * COMPUTES STEEL MODULUS OF
C * ELASTICITY RETENTION FACTOR
C * FOR EACH SECTION ELEMENT
C *****
C
      SUBROUTINE ELAST (Iet,TH,TC,GRAD,EH,EC)
C

```

```

      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION T1(100), T2(100), T3(100), T4(100)
      COMMON/SET2/ AE1(100), Io1(100), YE1(100), E1(100)
      COMMON/SET3/ AE2(100), Io2(100), YE2(100), E2(100)
      COMMON/SET4/ AE3(100), Io3(100), YE3(100), E3(100)
      COMMON/SET5/ AE4(100), Io4(100), YE4(100), E4(100)

C
C      TH  = hot flange temperature, degrees C
C      TC  = cold flange temperature, degrees C
C      GRAD = temperature gradient (linear) across steel section, deg.C/mm
C      EH  = modulus of elasticity retention factor at extreme hot fibre
C      EC  = modulus of elasticity retention factor at extreme cold fibre
C      T1, T2, T3, T4 are temperatures of section elements
C      E1, E2, E3, E4 are modulus retention factors for section elements
C      IET = indicator for the formulation of the modulus of elasticity
C           retention factor at elevated temperatures
C           1 for Gerlich (1995) formula, extended to 1000 degrees C
C           2 for Makelainen and Miller (1983) formula for steady-state tests
C           3 for Makelainen and Miller (1983) formula for transient tests
C
C      Calculate temperatures for each discretized section element
C
      DO 501 I=1,100
      T1(I)=TC+GRAD*YE1(I)
      T2(I)=TC+GRAD*YE2(I)
      T3(I)=TC+GRAD*YE3(I)
      T4(I)=TC+GRAD*YE4(I)
501 CONTINUE
C
C      Compute modulus retention factor for each section element
C
      IF (IET. NE. 1) GO TO 520
      EH=ELST1(TH)
      EC=ELST1(TC)
      DO 511 I=1,100
      E1(I)=ELST1(T1(I))
      E2(I)=ELST1(T2(I))
      E3(I)=ELST1(T3(I))
      E4(I)=ELST1(T4(I))
511 CONTINUE
      GO TO 599
C
520 IF (IET. NE. 2) GO TO 530
      EH=ELST2(TH)
      EC=ELST2(TC)
      DO 521 I=1,100
      E1(I)=ELST2(T1(I))
      E2(I)=ELST2(T2(I))
      E3(I)=ELST2(T3(I))
      E4(I)=ELST2(T4(I))
521 CONTINUE
      GO TO 599
C
530 IF (IET. NE. 3) GO TO 598
      EH=ELST3(TH)
      EC=ELST3(TC)
      DO 531 I=1,100
      E1(I)=ELST3(T1(I))
      E2(I)=ELST3(T2(I))
      E3(I)=ELST3(T3(I))
      E4(I)=ELST3(T4(I))
531 CONTINUE
      GO TO 599
C
598 WRITE (*,5001) IET
5001 FORMAT (5X,'UNKNOWN MODEL',I3,2X,'FOR MODULUS RETENTION')
      STOP

```

```

C
C 599 CONTINUE
C
C
C      RETURN
C      END
C
C
C      *****
C      * YIELD *
C      * COMPUTES STEEL STRENGTH *
C      * AT EXTREME FIBRES *
C      *****
C
C      SUBROUTINE YIELD (Fy,IFyt,TH,TC,Fyh,Fyc)
C
C      IMPLICIT REAL*8 (A-H,O-Z)
C
C      TH = hot flange temperature, degrees C
C      TC = cold flange temperature, degrees C
C      Fy = steel yield strength at room temperature
C      Fyh = steel yield strength at extreme hot fibre
C      Fyc = steel yield strength at extreme cold fibre
C      IFyt= indicator for the formulation of the yield strength retention
C            factor at elevated temperatures
C            1 for Gerlich (1995) formula, extended to 1000 degrees C
C            2 for Makelainen and Miller (1983) formula, extended to 1000 deg. C
C            3 for BS 5950: Part 8 formula, extended to 1000 deg. C
C
C      701 IF (IFyt. NE. 1) GO TO 702
C          Fyh=FYT1(TH)*FY
C          Fyc=FYT1(TC)*FY
C          GO TO 799
C
C      702 IF (IFyt. NE. 2) GO TO 703
C          Fyh=FYT2(TH)*FY
C          Fyc=FYT2(TC)*FY
C          GO TO 799
C
C      703 IF (IFyt. NE. 3) GO TO 798
C          Fyh=FYT3(TH)*FY
C          Fyc=FYT3(TC)*FY
C          GO TO 799
C
C      798 WRITE (*,7001) IFyt
C      7001 FORMAT (5X,'UNKNOWN MODEL',I3,2X,'FOR STRENGTH RETENTION')
C          STOP
C
C      799 CONTINUE
C
C
C      RETURN
C      END
C
C
C      *****
C      * GEOM *
C      * COMPUTES MODULUS-WEIGHTED *
C      * SECTION PROPERTIES *
C      *****
C
C      SUBROUTINE GEOM (Ao,CG1,CG3,CG4,WI1,A2,S3c,S3t,S4c,S4t)
C
C      IMPLICIT REAL*8 (A-H,O-Z)
C      COMMON/SET2/ AE1(100), Io1(100), YE1(100), E1(100)
C      COMMON/SET3/ AE2(100), Io2(100), YE2(100), E2(100)
C      COMMON/SET4/ AE3(100), Io3(100), YE3(100), E3(100)
C      COMMON/SET5/ AE4(100), Io4(100), YE4(100), E4(100)

```

```

C
C
C   Modulus-weighted section properties (for 4 types of sections):
C   A1, A2, A3, A4   = area of section,
C   CG1, CG3, CG4   = distance from section centroid to the outside face
C                   of cold flange,
C   WI1, WI3, WI4   = section moment of inertia,
C   S3c, S3t, S4c, S4t = section modulus in bending.
C
C
C   Compute modulus-weighted properties for unreduced unperforated section
C
C       A1=0.0
C       CG1=0.0
C       DO 811 I=1,100
C           DUM=E1(I)*AE1(I)
C           A1=A1+DUM
C           CG1=CG1+DUM*YE1(I)
811 CONTINUE
C       CG1=CG1/A1
C
C       WI1=0.0
C       DO 812 I=1,100
C           WI1=WI1+E1(I)*(Io1(I)+AE1(I)*(YE1(I)-CG1)**2)
812 CONTINUE
C
C   Compute modulus-weighted properties for reduced section in compression
C
C       A2=0.0
C       DO 821 I=1,100
C           A2=A2+E2(I)*AE2(I)
821 CONTINUE
C
C   Compute modulus-weighted properties for reduced section in bending
C   (hot flange compressed)
C
C       A3=0.0
C       CG3=0.0
C       DO 831 I=1,100
C           DUM=E3(I)*AE3(I)
C           A3=A3+DUM
C           CG3=CG3+DUM*YE3(I)
831 CONTINUE
C       CG3=CG3/A3
C
C       WI3=0.0
C       DO 832 I=1,100
C           WI3=WI3+E3(I)*(Io3(I)+AE3(I)*(YE3(I)-CG3)**2)
832 CONTINUE
C       S3c=WI3/(Ao-CG3)
C       S3t=WI3/CG3
C
C   Compute modulus-weighted properties for reduced section in bending
C   (cold flange compressed)
C
C       A4=0.0
C       CG4=0.0
C       DO 841 I=1,100
C           DUM=E4(I)*AE4(I)
C           A4=A4+DUM
C           CG4=CG4+DUM*YE4(I)
841 CONTINUE
C       CG4=CG4/A4
C
C       WI4=0.0
C       DO 842 I=1,100
C           WI4=WI4+E4(I)*(Io4(I)+AE4(I)*(YE4(I)-CG4)**2)
842 CONTINUE

```

```

      S4c=WI4/CG4
      S4t=WI4/(Ao-CG4)
C
C
      RETURN
      END
C
C
C
C *****
C * STEEL MODULUS OF ELASTICITY *
C * RETENTION FACTOR AT ELEV.TEMP.*
C * FORMULA 1 (Gerlich 1995) *
C *****
C
      DOUBLE PRECISION FUNCTION ELST1(T)
C
      IMPLICIT REAL*8 (A-H,O-Z)
C
      901 IF (T. GT. 650.) GO TO 902
      ELST1=1.-3.E-4*T+3.7E-7*T**2-6.1E-9*T**3+5.4E-12*T**4
      GO TO 999
C
      902 IF (T. GT. 1000.) GO TO 903
      ELST1=0.528-0.000428*T
      GO TO 999
C
      903 ELST1=0.1
C
C
      999 RETURN
      END
C
C
C *****
C * STEEL MODULUS OF ELASTICITY *
C * RETENTION FACTOR AT ELEV.TEMP.*
C * FORMULA 2 (Makelainen and *
C * Miller 1983, steady tests) *
C *****
C
      DOUBLE PRECISION FUNCTION ELST2(T)
C
      IMPLICIT REAL*8 (A-H,O-Z)
C
      901 IF (T. GT. 800.) GO TO 902
      ELST2=-0.46*DTANH((T-550.)/250.)+0.56
      GO TO 999
C
      902 IF (T. GT. 1000.) GO TO 903
      ELST2=0.65-0.00055*T
      GO TO 999
C
      903 ELST2=0.1
C
C
      999 RETURN
      END
C
C
C *****
C * STEEL MODULUS OF ELASTICITY *
C * RETENTION FACTOR AT ELEV.TEMP.*
C * FORMULA 3 (Makelainen and *
C * Miller 1983, transient tests) *
C *****
C
      DOUBLE PRECISION FUNCTION ELST3(T)
C

```

```

      IMPLICIT REAL*8 (A-H,O-Z)
C
901  IF (T. GT. 600.) GO TO 902
      ELST3=1.01-0.139**2.71828**(0.007*(T-346.))
      GO TO 999
C
902  IF (T. GT. 1000.) GO TO 903
      ELST3=0.3175-0.0002175*T
      GO TO 999
C
903  ELST3=0.1
C
C
999  RETURN
      END
C
C
C *****
C * STEEL YIELD STRENGTH *
C * RETENTION FACTOR AT ELEV.TEMP.*
C * FORMULA 1 (Gerlich 1995) *
C *****
C
      DOUBLE PRECISION FUNCTION FYT1(T)
C
      IMPLICIT REAL*8 (A-H,O-Z)
C
901  IF (T. GT. 650.) GO TO 902
      FYT1=1.-5.3E-4*T+4.E-6*T**2-1.9E-8*T**3+1.7E-11*T**4
      GO TO 999
C
902  IF (T. GT. 1000.) GO TO 903
      FYT1=0.464-0.000464*T
      GO TO 999
C
903  FYT1=0.
C
C
999  RETURN
      END
C
C
C *****
C * STEEL YIELD STRENGTH *
C * RETENTION FACTOR AT ELEV.TEMP.*
C * FORMULA 2 (Makelainen and *
C * Miller 1983) *
C *****
C
      DOUBLE PRECISION FUNCTION FYT2(T)
C
      IMPLICIT REAL*8 (A-H,O-Z)
C
901  IF (T. GT. 500.) GO TO 902
      FYT2=1.088-0.1314*2.71828**(0.0047*(T-148.3))
      GO TO 999
C
902  IF (T. GT. 800.) GO TO 903
      FYT2=104.*(1.-T/1135.)/(T-356.)
      GO TO 999
C
903  IF (T. GT. 1000.) GO TO 904
      FYT2=0.345-0.000345*T
      GO TO 999
C
904  FYT2=0.
C
C

```

```

999 RETURN
END

C
C
C *****
C * STEEL YIELD STRENGTH *
C * RETENTION FACTOR AT ELEV.TEMP.*
C * FORMULA 3 (BS 5950 : Part 8) *
C *****
C
C DOUBLE PRECISION FUNCTION FYT3(T)
C
C IMPLICIT REAL*8 (A-H,O-Z)
C
901 IF (T. GT. 100.) GO TO 902
    FYT3=1.
    GO TO 999
C
902 IF (T. GT. 200.) GO TO 903
    FYT3=1.055-0.00055*T
    GO TO 999
C
903 IF (T. GT. 250.) GO TO 904
    FYT3=1.165-0.0011*T
    GO TO 999
C
904 IF (T. GT. 300.) GO TO 905
    FYT3=1.17-0.00112*T
    GO TO 999
C
905 IF (T. GT. 350.) GO TO 906
    FYT3=1.29-0.00152*T
    GO TO 999
C
906 IF (T. GT. 400.) GO TO 907
    FYT3=1.304-0.00156*T
    GO TO 999
C
907 IF (T. GT. 450.) GO TO 908
    FYT3=1.52-0.0021*T
    GO TO 999
C
908 IF (T. GT. 500.) GO TO 909
    FYT3=1.511-0.00208*T
    GO TO 999
C
909 IF (T. GT. 550.) GO TO 910
    FYT3=1.481-0.00202*T
    GO TO 999
C
910 IF (T. GT. 600.) GO TO 911
    FYT3=1.481-0.00202*T
    GO TO 999
C
911 IF (T. GT. 1000.) GO TO 912
    FYT3=0.6725-0.0006725*T
    GO TO 999
C
912 FYT3=0.
C
C
999 RETURN
END

```

C.6. References

1. Alfawakhiri, F., and Sultan, M. A., "Fire Resistance of Loadbearing LSF Assemblies", *Proceedings of the 15th International Specialty Conference on Cold-Formed Steel Structures*, St. Louis, MO, October 2000.
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8. S136-94, *Cold Formed Steel Structural Members*, Canadian Standards Association, Etobicoke, ON, December 1994.

Figure C.1. Flowchart of STUD program.

Figure C.2. Thermal Elongation of Steel.

Figure C.3. Retention Factors for Steel Modulus of Elasticity at Elevated Temperatures.

Figure C.4. Reduction of Steel Yield Strength at Elevated Temperatures.

Figure C.5. Steel Frame Fabrication Layout (LSF Wall SFF-1).

Figure C.6. Horizontal and Vertical Cross-Section Details (LSF Wall SFF-1).

Figure C.7. Simulated and Measured Lateral Deflections at Stud Mid-Height.

Appendix D

Computer Program JOIST

User Manual

D.1. Introduction

Numerical simulations help in tracing the complex interaction of thermal and structural phenomena in construction assemblies subjected to fire attack. In this context, the JOIST program was developed to investigate the structural behaviour of cold-formed steel joists in unrestrained lightweight steel-framed (LSF) floors exposed to fire. The program has been used for retrospective simulations of five standard fire resistance tests (Sultan et al 1998). The program computes deformation histories of the heated joists and predicts their fire resistance by evaluating their moment resistance capacity and comparing it to the mid-span moment due to applied load (at every time history step). The program also generates moment-curvature relationships, deformation, curvature and stress profiles at user-specified locations and times.

Computational techniques are becoming increasingly important as research and design tools in structural fire protection. JOIST helps to produce an 'educated guess' of expected fire resistance in situations where results of standard fire tests are not available or not applicable (e.g. when the size of the structure precludes testing or when non-standard fire exposure must be considered). JOIST is a research tool that can be used to optimize future experimental programs on the fire resistance of LSF floors. Numerical results provide additional information that helps in the analysis of test data. JOIST simulations can also be used for parametric studies.

D.2. Program Description

The source code JOIST is presented Section D.5. The implemented algorithm for computing deflections and bending moments at critical sections closely follows procedures described by Alfawakhiri and Sultan (2001). The explanatory notes within the source code provide brief descriptions of the computational routines and the parameters used in the program.

JOIST was successfully compiled and tested using Digital Visual Fortran Version 5.0. The executable file occupies 380 KB of storage space. The program code is compliant with standard Fortran 77, and therefore, older versions of Fortran compilers can also be used.

An input file, in ASCII text format, has to be generated and saved before program execution. At start, the program prompts the user for the names of the input file and the output file. These names should be entered on the keyboard during program execution. The program will create an output file with the specified name and write down the output data to that file. The output file is an ASCII text file, which can be easily imported into a spreadsheet application for post-processing.

The flowchart for JOIST is shown in Figure D.1. The main program opens the input and output files, and, for every time-history step, computes joist mid-span deflections, bending moments, failure criteria, and writes the results to the output file. In addition to the main program, JOIST contains six subroutines: DATIN, CSECT, BOW, ELAST, GEOM and YIELD.

Subroutine DATIN reads the input file and records the input parameters to memory. These parameters describe joist dimensions, steel properties, applied vertical load, lateral deformation conditions, section of interest (for detailed output) and time-history of temperatures at hot and cold flanges. The required format of the input file is described in the next section.

Subroutine CSECT performs the discretization of lipped-C-shaped steel joist sections. First, the overall dimensions are determined for four types of cross-sections: unreduced, effective in compression, effective in bending with hot flange compressed and effective in bending with cold flange compressed. The width of compression elements in effective joist cross-sections is determined in accordance with Clause 5.6.2 of S136-94. For perforated sections in compression, the web is considered to consist of two unstiffened elements, one on each side of perforation, according to Clause 6.8.1 of S136-94. The effective cross-section dimensions are assumed to be insensitive to temperature, i.e. they are based on steel properties at room temperature and compressive stress equal to steel yield strength. Secondly, each of the four sections is divided to 100 finite elements. Finally, the subroutine computes the geometry parameters (area, distance to reference axis, etc.) of the finite elements for every case and records them to memory.

Subroutine BOW computes the curvature FI of the joist due to 'stress-free' thermal bowing, based on the difference in thermal elongation strain between the hot and cold flanges. The user can choose from three models for steel thermal elongation strain, suggested by Lie (1992), Lawson and Newman (1990) and Makelainen and Miller (1983), that are contained in the current version of the subroutine. These models are illustrated in Figure D.2. Other steel thermal strain models can be easily added to the subroutine to extend its applicability to specific steel properties or in order to conduct parametric studies on the effect of thermal elongation on fire resistance.

Subroutine ELAST calculates the temperatures of all finite elements for sections specified by subroutine CSECT, assuming a linear temperature gradient between hot and cold flanges. Based on these temperatures, the subroutine computes the temperature-dependent modulus of elasticity of steel for each finite element. The user can choose from three models for elastic modulus retention (at elevated temperatures), suggested by Gerlich (1995) and Makelainen and Miller (1983), that are implemented in the current version of the subroutine and associated functions. These models are illustrated in Figure D.3. Other steel elastic modulus models can be easily added to the subroutine to extend its applicability to specific steel properties or in order to conduct parametric studies on the effect of steel elastic modulus retention (at elevated temperatures) on fire resistance.

Subroutine GEOM computes the temperature-dependent modulus-weighted properties (area, moment of inertia, section moduli in bending) for sections specified by subroutine CSECT, based on elastic moduli of finite elements specified by subroutine ELAST.

Subroutine YIELD computes the temperature-dependent steel yield strength at all finite elements for the effective section in bending with cold flange compressed, specified by subroutine CSECT. The user can choose from three models for steel yield strength at elevated temperatures, suggested by Gerlich (1995), Makelainen and Miller (1983) and BS 5950, that are contained in the current version of the subroutine and the associated functions. These models are illustrated in Figure D.4. Other steel yield strength formulas can be easily added to the subroutine to extend its applicability to specific steel properties or in order to conduct parametric studies on the effect of steel strength retention (at elevated temperatures) on fire resistance.

JOIST executes structural analysis procedures for every time step (and respective hot and cold flange temperature combination) specified in the input file. At each step, the program evaluates the moment-relationship for the joist section, the deflected shape of the joist and checks the mid-span section for moment resistance capacity. For each time step, the program writes to the output file the time TSi, the average temperature of the joist Ta, the temperature difference between the hot and cold flanges Td, the reduced mid-span deflection DRth due to thermal bowing, the mid-span deflection due to the deterioration of steel mechanical properties Dst, total mid-span deflection D, corrected

mid-span deflection D_{cor} (equal to D , but not less than D in the previous time step), moment resistance of joist section RM , failure criterion $CRIT$ (ratio of mid-span moment, due to applied loads and EM , to RM), and corrected deflection D_{lc} of the joist at user-specified section at distance z_1 from the left support. For user-specified time step $PRNT$, the program also writes to the output file the moment-curvature relationship (curvature array $PRNT1$ and moment array $PRNT3$), moment/curvature/deflection profiles along the joist (array z for distances from the left support, moment array $PRNT4$, curvature array $PRNT5$ and deflection array $PRNT6$), and stress profile of joist section at user-specified distance z_1 from the left support (array $PRNT7$ for distances from the extreme bottom fibre and stress array $PRNT8$).

The bending moment resistance RM of the joist is based on the inelastic capacity of the heated section, where tensile strains are not limited, while the compressive strains are limited to the yield strain. This formulation is in line with Clauses 6.4.2.1 and 6.4.2.2 of S136-94. The section is considered to fail at the time when $CRIT$ exceeds unity. This time is indicative of the fire resistance of the LSF floor.

It should be noted, that JOIST procedures, for the evaluation of deflections, explicitly model phenomena, observed in full-scale fire resistance tests, that can be associated with creep and stress relaxation processes at elevated temperatures. Therefore, the joist corrected deflections, D_{cor} and D_{lc} , at any time step are not allowed to be less than in the previous time step.

It should be noted that JOIST is a unit-sensitive program. All input for temperatures must be in $^{\circ}C$, which are required for all models for temperature-dependent steel properties within the program. Any appropriate unit can be used for time input. A set of consistent units should be used for all other input parameters. The recommended unit set consists of dimensions in mm, steel modulus of elasticity and yield strength in MPa, and vertical uniformly-distributed load in N/mm (in this case, the deflection, stress and bending moment values in the output will be in mm, MPa and Nmm, respectively). Using other sets of units may require changes in the output format.

D.3. Input File Format

The order of input data by sequence of parameters needed by JOIST is as follows:

1. Title line for problem identification (one line of up to 80 alphanumeric characters, including spaces).
2. Line, describing the geometry of lipped-C-section steel joist, consisting of seven parameters separated by commas:
 A_o , B_o , C_o , t_s , R_o , A_p , H .

3. Line, describing steel properties, consisting of five parameters separated by commas:
E, IEt, Fy, IFyt, Iext.
4. Line, describing parameters for structural analysis, consisting of five parameters separated by commas:
EP, RCLD, NTS, z1, PRNT.
5. NTS lines (one line per time step), describing time-history of temperatures at hot and cold flanges, each consisting of three parameters separated by commas:
TSi, TH, TC.

Integer values should be entered for parameters, starting with letters I-N. Real values should be entered for all other parameters.

Ao = out to out depth of joist section.

Bo = out to out width of flange.

Co = out to out width of lip (flange stiffener).

ts = black metal thickness.

Ro = inside bend radius.

Ap = width of web perforation.

H = joist span length.

E = steel modulus of elasticity at room temperature.

IEt = indicator for the formulation of steel modulus of elasticity retention factor at elevated temperatures.
1 for Gerlich (1995) formula, extended to 1000 °C.
2 for Makelainen and Miller (1983) formula, for steady-state tests, extended to 1000 °C.
3 for Makelainen and Miller (1983) formula, for transient tests, extended to 1000 °C.

Fy = steel yield strength at room temperature.

IFyt = indicator for the formulation of steel yield strength retention factor at elevated temperatures.
1 for Gerlich (1995) formula, extended to 1000 °C.
2 for Makelainen and Miller (1983) formula, extended to 1000 °C.

3 for BS 5950 formulation for 0.5% strain, extended to 1000 °C.

Iext = indicator for the formulation of steel thermal elongation strain.
 1 for Lie (1992) formula, extended to 1000 °C.
 2 for Lawson and Newman (1990) formula, extended to 1000 °C.
 3 for Makelainen and Miller (1983) formula, extended to 1000 °C.

P = tributary uniformly distributed vertical load for one joist (force per length units).

RCLD = reduction coefficient for thermal bowing deflection, which depends on the extent

of non-linearity in thermal strain gradient across joist section.

= 1.0 for linear thermal strain gradient (stress-free condition).

Values of 0.8-1.0 are recommended for scenarios where a non-linear thermal strain

gradient across joist section can be expected.

Non-linear thermal strain gradients cause reduction to the 'stress-free' thermal bowing curvature and deflection. Non-linear thermal strain gradients also cause an

internal state of stress in the joist section, with hot flange in compression and cold flange in tension. This state of stress has an unloading effect as illustrated in Figure D.5. The program models this internal state of stress through the application of artificial external end moments EM. Whenever $RCLD < 1$ is specified, the program will use this coefficient to reduce the deflection due to thermal bowing. The program will also reduce the mid-span moment, due to applied load, by EM.

NTS = number of lines (time steps), describing time-history of temperatures at hot and cold flanges.

z1 = distance (from the left support) of the joist section for which the deflection and other detailed information will be printed out.

PRNT = time step number (TSi) for which the detailed information is to be printed out.

Enter negative value if no detailed information is requested.

If a positive value is entered that matches one of the time steps TSi values, the program writes to the output file the following information (with regard to PRNT time step and section at z1):

PRNT1 = curvature array for moment-curvature relationship

PRNT3 = moment array for moment-curvature relationship

z = array of distances from the left support to mid-span (form moment, curvature and deflection profiles along the joist)

PRNT4 = array of moments for moment profile

PRNT5 = array of curvatures for curvature profile
 PRNT6 = array of deflections for deflection profile
 PRNT7 = array of distances from the extreme bottom fibre (for stress profile at section specified at distance $z1$ from the left support).
 PRNT8 = array of stresses for stress profile at section specified at distance $z1$ from the left support).

TSi = time, or time step number (identification number for temperature combination).

TH = hot flange temperature (in °C).

TC = cold flange temperature (in °C).

D.4. Numerical Example

A standard fire resistance test (according to CAN/ULC-S101-M89) was conducted recently on LSF floor assembly FF-25 (Sultan et al 1998). The assembly consisted of cold-formed steel joists, each spanning 3805 mm, spaced 406 mm o.c., with appropriate bridging and blocking that ensured the lateral stability in the plane of the floor. Figure D.6 shows the cross-sectional details of the floor specimen. Each steel joist had a C-shaped cross-section, nominally, 203.2 mm deep by 41.3 mm wide, with 12.7-mm flange-stiffening lips and base metal thickness of 1.214 mm. The minimum specified steel yield strength was 230 MPa.

Temperature histories for hot and cold flanges were measured and recorded (at 0.5-minute intervals) during the fire resistance test. Vertical load of 2.945 kN/m² (in addition to assembly self-weight) was held constant for the duration of the test. The floor failed after 46 minutes of fire exposure by losing its ability to sustain the applied load. The joist failure mode was the compressive failure of the cold flange near joist mid-span.

The use of JOIST is illustrated here by the following 47.5-minute structural simulation for floor FF-25. The floor is modeled by a single simply-supported joist with uniformly distributed load of 1.34 N/mm. Steel modulus of elasticity at room temperature is assumed equal to 203000 MPa. Retention factors suggested by Gerlich (1995), for steel yield strength and modulus of elasticity at elevated temperatures, are adopted in the simulation. Lie (1992) formula is used for the evaluation of thermal strains. The reduction factor RCLD=0.8 for thermal bowing is adopted in this simulation.

The input and output files are listed in the following subsections. The simulated mid-span deflection is shown in Figure D.7 compared with the average mid-span deflection measured during the test. The output file results show that the value of CRIT exceeds unity at 45 minutes, which indicates that the simulated failure occurs after 44.5 minutes of fire exposure. This is a conservative and fairly accurate estimate of fire resistance.

Detailed data was obtained for the 45-minute time step. The calculated moment-curvature relationship is shown in Figure D.8. The mid-span section stress profile is shown in Figure D.9.

D.4.1. Input File

```
LSF FLOOR FF-25 (JOIST RUN) Temp. Histories from Fire Test
203.2,41.3,12.7,1.214,2.428,0.,3805.
203000.,1,230.,1,1
1.34,0.8,96,1902.5,45.
0,23,23.075
0.5,22.975,23.075
1,23,23.075
1.5,23.3,23.1
2,30.525,23.125
2.5,44.2,23.175
3,60.8,23.475
3.5,81.05,24.65
4,88.475,26.625
4.5,90.025,28.45
5,92.425,30.7
5.5,92.925,33.4
6,93.125,36.325
6.5,92.325,39.525
7,92.5,42.525
7.5,92.47501,45.325
8,92.4,48
8.5,92.52499,50.35
9,92.625,52.375
9.5,92.8,54.425
10,92.95,56.575
10.5,93.025,58.275
11,92.975,59.925
11.5,93,61.45
12,92.85001,62.775
12.5,92.825,63.95
13,92.475,64.85
13.5,92.64999,65.825
14,92.975,66.52499
14.5,94.05,67.425
15,93.875,68.05
15.5,94.1,68.75
16,92.64999,69.35
16.5,93.89999,69.825
17,96.97501,70.125
17.5,101.975,70.45
18,111.725,70.825
18.5,117.5,71.125
19,134.95,71.5
19.5,148.425,72.2
20,163.475,73.05
```

20.5,179.3,73.375
21,199.4,73.025
21.5,216.425,72.625
22,236.3,72.575
22.5,255.525,72.575
23,273.825,72.425
23.5,292.575,72.27499
24,310.025,72.125
24.5,329.05,72
25,344.95,71.975
25.5,363.2,72.05
26,380.275,72.225
26.5,397.5,72.4
27,409.725,72.675
27.5,421.625,73.10001
28,434.2,73.625
28.5,451.3,74.275
29,465.2,74.97501
29.5,486.05,75.825
30,500.8,76.675
30.5,516.325,77.625
31,529.325,78.525
31.5,545.825,79.575
32,557.925,80.425
32.5,567.425,81.425
33,579.875,82.65
33.5,591.25,83.875
34,603.25,85.675
34.5,613.35,88.55
35,633.675,92.125
35.5,644.85,95.95
36,673.025,100.05
36.5,688.45,104.3
37,735.7,108.5
37.5,732.225,113.25
38,785.95,118.525
38.5,777.775,123.825
39,821.775,129.875
39.5,798.45,136.375
40,837.325,143.75
40.5,807.475,151.95
41,841.8,162.3
41.5,814.675,171.925
42,842.7,184.975
42.5,816.8,197.4
43,843.425,210.925
43.5,828.425,225.625
44,840.225,246.075
44.5,837.375,262.925
45,846.6,286.175
45.5,864.525,311.175
46,844.125,341.725
46.5,856.375,366.325
47,840.4,394.75

47.5,792.575,266.625

D.4.2. Output File

1

```

LSF FLOOR FF-25 (JOIST RUN) Temp. Histories from Fire Test
  TSi    Ta    Td    DRth    Dst    D    Dcor    RM    CRIT    D1c
  0.0    23.0    0.0    0.0    0.1    0.1    0.1    0.454E+07    0.534    0.1
  0.5    23.0    0.0    0.0    0.1    0.1    0.1    0.454E+07    0.534    0.1
  1.0    23.0    0.0    0.0    0.1    0.1    0.1    0.454E+07    0.534    0.1
  1.5    23.2    0.2    0.0    0.1    0.1    0.1    0.454E+07    0.534    0.1
  2.0    26.8    7.4    0.6    0.1    0.7    0.7    0.454E+07    0.527    0.7
  2.5    33.7    21.0    1.8    0.1    1.9    1.9    0.453E+07    0.512    1.9
  3.0    42.1    37.3    3.2    0.1    3.3    3.3    0.453E+07    0.496    3.3
  3.5    52.8    56.4    4.9    0.1    5.1    5.1    0.452E+07    0.476    5.1
  4.0    57.5    61.8    5.4    0.2    5.5    5.5    0.451E+07    0.471    5.5
  4.5    59.2    61.6    5.4    0.2    5.5    5.5    0.451E+07    0.471    5.5
  5.0    61.6    61.7    5.4    0.2    5.6    5.6    0.451E+07    0.472    5.6
  5.5    63.2    59.5    5.2    0.2    5.4    5.6    0.450E+07    0.474    5.6
  6.0    64.7    56.8    5.0    0.2    5.1    5.6    0.450E+07    0.478    5.6
  6.5    65.9    52.8    4.6    0.2    4.8    5.6    0.450E+07    0.482    5.6
  7.0    67.5    50.0    4.4    0.2    4.6    5.6    0.449E+07    0.486    5.6
  7.5    68.9    47.2    4.1    0.2    4.3    5.6    0.449E+07    0.489    5.6
  8.0    70.2    44.4    3.9    0.2    4.1    5.6    0.449E+07    0.492    5.6
  8.5    71.4    42.2    3.7    0.2    3.9    5.6    0.449E+07    0.495    5.6
  9.0    72.5    40.3    3.5    0.2    3.7    5.6    0.448E+07    0.497    5.6
  9.5    73.6    38.4    3.4    0.2    3.6    5.6    0.448E+07    0.499    5.6
 10.0    74.8    36.4    3.2    0.2    3.4    5.6    0.448E+07    0.502    5.6
 10.5    75.7    34.8    3.0    0.2    3.3    5.6    0.448E+07    0.504    5.6
 11.0    76.4    33.0    2.9    0.2    3.1    5.6    0.448E+07    0.506    5.6
 11.5    77.2    31.5    2.8    0.2    3.0    5.6    0.448E+07    0.508    5.6
 12.0    77.8    30.1    2.6    0.2    2.9    5.6    0.448E+07    0.509    5.6
 12.5    78.4    28.9    2.5    0.2    2.8    5.6    0.447E+07    0.511    5.6
 13.0    78.7    27.6    2.4    0.2    2.6    5.6    0.447E+07    0.512    5.6
 13.5    79.2    26.8    2.4    0.2    2.6    5.6    0.447E+07    0.513    5.6
 14.0    79.7    26.5    2.3    0.2    2.5    5.6    0.447E+07    0.513    5.6
 14.5    80.7    26.6    2.3    0.2    2.6    5.6    0.447E+07    0.513    5.6
 15.0    81.0    25.8    2.3    0.2    2.5    5.6    0.447E+07    0.514    5.6
 15.5    81.4    25.3    2.2    0.2    2.5    5.6    0.447E+07    0.515    5.6
 16.0    81.0    23.3    2.0    0.2    2.3    5.6    0.447E+07    0.517    5.6
 16.5    81.9    24.1    2.1    0.2    2.3    5.6    0.447E+07    0.516    5.6
 17.0    83.6    26.9    2.4    0.2    2.6    5.6    0.447E+07    0.513    5.6
 17.5    86.2    31.5    2.8    0.2    3.0    5.6    0.447E+07    0.509    5.6
 18.0    91.3    40.9    3.6    0.3    3.9    5.6    0.446E+07    0.499    5.6
 18.5    94.3    46.4    4.1    0.3    4.4    5.6    0.446E+07    0.493    5.6
 19.0    103.2    63.4    5.6    0.3    5.9    5.9    0.445E+07    0.476    5.9
 19.5    110.3    76.2    6.8    0.3    7.1    7.1    0.444E+07    0.463    7.1
 20.0    118.3    90.4    8.0    0.4    8.4    8.4    0.443E+07    0.448    8.4
 20.5    126.3    105.9    9.4    0.4    9.9    9.9    0.442E+07    0.433    9.9
 21.0    136.2    126.4    11.3    0.5    11.8    11.8    0.441E+07    0.413    11.8
 21.5    144.5    143.8    12.9    0.6    13.4    13.4    0.439E+07    0.396    13.4
 22.0    154.4    163.7    14.7    0.6    15.4    15.4    0.437E+07    0.377    15.4
 22.5    164.1    182.9    16.5    0.7    17.2    17.2    0.434E+07    0.359    17.2
 23.0    173.1    201.4    18.2    0.8    19.0    19.0    0.431E+07    0.343    19.0
 23.5    182.4    220.3    20.0    0.9    20.9    20.9    0.427E+07    0.327    20.9
 24.0    191.1    237.9    21.6    1.0    22.7    22.7    0.423E+07    0.313    22.7
 24.5    200.5    257.1    23.4    1.2    24.6    24.6    0.419E+07    0.298    24.6
 25.0    208.5    273.0    25.0    1.3    26.3    26.3    0.414E+07    0.287    26.3

```

25.5	217.6	291.1	26.7	1.5	28.2	28.2	0.408E+07	0.275	28.2
26.0	226.3	308.0	28.3	1.6	29.9	29.9	0.402E+07	0.265	29.9
26.5	234.9	325.1	30.0	1.8	31.8	31.8	0.395E+07	0.255	31.8
27.0	241.2	337.1	31.1	1.9	33.1	33.1	0.390E+07	0.250	33.1
27.5	247.4	348.5	32.3	2.1	34.3	34.3	0.385E+07	0.245	34.3
28.0	253.9	360.6	33.4	2.3	35.7	35.7	0.378E+07	0.240	35.7
28.5	262.8	377.0	35.1	2.5	37.6	37.6	0.370E+07	0.235	37.6
29.0	270.1	390.2	36.4	2.7	39.1	39.1	0.362E+07	0.233	39.1
29.5	280.9	410.2	38.4	3.1	41.4	41.4	0.350E+07	0.230	41.4
30.0	288.7	424.1	39.8	3.4	43.1	43.1	0.341E+07	0.231	43.1
30.5	297.0	438.7	41.2	3.7	44.9	44.9	0.331E+07	0.233	44.9
31.0	303.9	450.8	42.4	4.0	46.4	46.4	0.322E+07	0.236	46.4
31.5	312.7	466.3	44.0	4.4	48.4	48.4	0.311E+07	0.241	48.4
32.0	319.2	477.5	45.2	4.7	49.9	49.9	0.302E+07	0.247	49.9
32.5	324.4	486.0	46.0	5.0	51.0	51.0	0.296E+07	0.253	51.0
33.0	331.3	497.2	47.2	5.4	52.6	52.6	0.287E+07	0.262	52.6
33.5	337.6	507.4	48.3	5.7	54.0	54.0	0.279E+07	0.272	54.0
34.0	344.5	517.6	49.3	6.2	55.5	55.5	0.271E+07	0.285	55.5
34.5	350.9	524.8	50.1	6.6	56.7	56.7	0.264E+07	0.298	56.7
35.0	362.9	541.5	51.9	7.4	59.3	59.3	0.251E+07	0.326	59.3
35.5	370.4	548.9	52.7	8.0	60.7	60.7	0.244E+07	0.346	60.7
36.0	386.5	573.0	55.3	9.0	64.3	64.3	0.230E+07	0.376	64.3
36.5	396.4	584.2	56.5	9.5	66.1	66.1	0.223E+07	0.392	66.1
37.0	422.1	627.2	61.2	11.0	72.2	72.2	0.203E+07	0.428	72.2
37.5	422.7	619.0	60.4	10.9	71.3	72.2	0.204E+07	0.434	72.2
38.0	452.2	667.4	65.7	12.9	78.6	78.6	0.183E+07	0.484	78.6
38.5	450.8	653.9	64.3	12.7	77.0	78.6	0.185E+07	0.487	78.6
39.0	475.8	691.9	68.5	14.9	83.4	83.4	0.168E+07	0.541	83.4
39.5	467.4	662.1	65.4	13.9	79.3	83.4	0.175E+07	0.531	83.4
40.0	490.5	693.6	69.0	16.3	85.3	85.3	0.160E+07	0.590	85.3
40.5	479.7	655.5	65.0	14.9	79.9	85.3	0.169E+07	0.575	85.3
41.0	502.0	679.5	67.8	17.6	85.4	85.4	0.155E+07	0.640	85.4
41.5	493.3	642.8	64.0	16.2	80.2	85.4	0.163E+07	0.629	85.4
42.0	513.8	657.7	65.9	19.2	85.1	85.4	0.151E+07	0.700	85.4
42.5	507.1	619.4	61.9	17.9	79.8	85.4	0.158E+07	0.696	85.4
43.0	527.2	632.5	63.6	21.9	85.5	85.5	0.146E+07	0.772	85.5
43.5	527.0	602.8	60.6	21.9	82.4	85.5	0.148E+07	0.790	85.5
44.0	543.1	594.2	60.0	27.2	87.2	87.2	0.140E+07	0.873	87.2
44.5	550.1	574.5	58.1	31.2	89.3	89.3	0.137E+07	0.923	89.3
45.0	566.4	560.4	57.0	50.0	107.0	107.0	0.129E+07	1.025	107.0
45.5	587.9	553.3	56.6	2006.0	2062.6	2062.6	0.118E+07	1.171	2062.6
46.0	592.9	502.4	51.4	2531.4	2582.9	2582.9	0.118E+07	1.247	2582.9
46.5	611.4	490.1	50.4	8092.8	8143.2	8143.2	0.109E+07	1.402	8143.2
47.0	617.6	445.6	45.9	7330.4	7376.4	8143.2	0.107E+07	1.496	8143.2
47.5	529.6	526.0	52.9	23.2	76.1	8143.2	0.152E+07	0.857	8143.2

DETAILED DATA FOR TIME STEP 45.0

PRNT1	PRNT3	z	PRNT4	PRNT5	PRNT6	PRNT7	PRNT8
0.0000E+00	0.000E+00	0.0	-0.110E+07	-0.7869E-05	0.0	203.2	-194.3
0.1314E-05	0.184E+06	19.0	-0.105E+07	-0.7525E-05	0.5	202.6	-193.8
0.2627E-05	0.368E+06	38.0	-0.101E+07	-0.7184E-05	1.0	201.5	-192.8
0.3941E-05	0.531E+06	57.1	-0.960E+06	-0.6847E-05	1.6	199.0	-190.6
0.5255E-05	0.635E+06	76.1	-0.913E+06	-0.6513E-05	2.1	197.9	-189.6
0.6568E-05	0.717E+06	95.1	-0.867E+06	-0.6182E-05	2.6	196.7	-180.7
0.7882E-05	0.785E+06	114.2	-0.821E+06	-0.5855E-05	3.1	195.6	-168.3
0.9196E-05	0.841E+06	133.2	-0.775E+06	-0.5532E-05	3.7	194.5	-156.1
0.1051E-04	0.888E+06	152.2	-0.731E+06	-0.5212E-05	4.2	193.3	-143.9
0.1182E-04	0.928E+06	171.2	-0.686E+06	-0.4895E-05	4.8	192.2	-131.8
0.1314E-04	0.963E+06	190.3	-0.642E+06	-0.4582E-05	5.3	191.1	-119.8
0.1445E-04	0.994E+06	209.3	-0.599E+06	-0.4272E-05	5.8	198.3	-190.0

0.1576E-04	0.102E+07	228.3	-0.556E+06	-0.3966E-05	6.4	195.9	-171.5
0.1708E-04	0.105E+07	247.3	-0.514E+06	-0.3663E-05	6.9	193.4	-145.0
0.1839E-04	0.107E+07	266.4	-0.472E+06	-0.3364E-05	7.5	191.0	-118.9
0.1971E-04	0.109E+07	285.4	-0.430E+06	-0.3068E-05	8.0	188.5	-93.4
0.2102E-04	0.111E+07	304.4	-0.389E+06	-0.2776E-05	8.6	186.1	-68.3
0.2233E-04	0.113E+07	323.4	-0.349E+06	-0.2487E-05	9.1	183.6	-43.8
0.2365E-04	0.115E+07	342.4	-0.309E+06	-0.2202E-05	9.7	181.2	-19.7
0.2496E-04	0.116E+07	361.5	-0.269E+06	-0.1920E-05	10.2	178.7	3.7
0.2627E-04	0.117E+07	380.5	-0.230E+06	-0.1641E-05	10.8	176.3	26.6
0.2759E-04	0.119E+07	399.5	-0.192E+06	-0.1366E-05	11.3	173.8	48.9
0.2890E-04	0.120E+07	418.5	-0.153E+06	-0.1095E-05	11.9	171.4	70.6
0.3021E-04	0.121E+07	437.6	-0.116E+06	-0.8265E-06	12.4	168.9	91.7
0.3153E-04	0.122E+07	456.6	-0.788E+05	-0.5618E-06	13.0	166.5	112.1
0.3284E-04	0.123E+07	475.6	-0.421E+05	-0.3006E-06	13.5	164.0	131.9
0.3416E-04	0.124E+07	494.6	-0.600E+04	-0.4283E-07	14.1	161.6	148.4
0.3547E-04	0.125E+07	513.7	0.296E+05	0.2115E-06	14.6	159.2	145.1
0.3678E-04	0.125E+07	532.7	0.648E+05	0.4623E-06	15.2	156.7	141.8
0.3810E-04	0.126E+07	551.7	0.995E+05	0.7097E-06	15.7	154.3	138.4
0.3941E-04	0.127E+07	570.7	0.134E+06	0.9537E-06	16.3	151.8	135.0
0.4072E-04	0.128E+07	589.8	0.167E+06	0.1194E-05	16.8	149.4	131.5
0.4204E-04	0.128E+07	608.8	0.201E+06	0.1431E-05	17.4	146.9	128.0
0.4335E-04	0.129E+07	627.8	0.233E+06	0.1665E-05	17.9	144.5	124.5
0.4467E-04	0.129E+07	646.8	0.266E+06	0.1895E-05	18.5	142.0	121.0
0.4598E-04	0.130E+07	665.9	0.297E+06	0.2121E-05	19.0	139.6	117.4
0.4729E-04	0.130E+07	684.9	0.329E+06	0.2345E-05	19.6	137.1	113.8
0.4861E-04	0.130E+07	703.9	0.359E+06	0.2564E-05	20.1	134.7	110.3
0.4992E-04	0.131E+07	722.9	0.390E+06	0.2800E-05	20.7	132.2	106.7
0.5123E-04	0.131E+07	742.0	0.420E+06	0.3041E-05	21.2	129.8	103.1
0.5255E-04	0.131E+07	761.0	0.449E+06	0.3278E-05	21.8	127.3	99.6
0.5386E-04	0.131E+07	780.0	0.478E+06	0.3510E-05	22.3	124.9	96.0
0.5517E-04	0.131E+07	799.0	0.506E+06	0.3739E-05	22.8	122.4	92.5
0.5649E-04	0.132E+07	818.1	0.534E+06	0.3977E-05	23.4	120.0	89.0
0.5780E-04	0.132E+07	837.1	0.561E+06	0.4324E-05	23.9	117.5	85.5
0.5912E-04	0.132E+07	856.1	0.588E+06	0.4666E-05	24.5	115.1	82.1
0.6043E-04	0.132E+07	875.1	0.615E+06	0.5001E-05	25.0	112.6	78.8
0.6174E-04	0.132E+07	894.2	0.641E+06	0.5349E-05	25.5	110.2	75.5
0.6306E-04	0.132E+07	913.2	0.666E+06	0.5754E-05	26.1	107.7	72.2
0.6437E-04	0.132E+07	932.2	0.691E+06	0.6151E-05	26.6	105.3	69.1
0.6568E-04	0.133E+07	951.2	0.716E+06	0.6541E-05	27.1	102.8	66.0
0.6700E-04	0.133E+07	970.3	0.740E+06	0.7002E-05	27.7	100.4	63.0
0.6831E-04	0.133E+07	989.3	0.763E+06	0.7460E-05	28.2	97.9	60.1
0.6963E-04	0.133E+07	1008.3	0.786E+06	0.7914E-05	28.7	95.5	57.3
0.7094E-04	0.133E+07	1027.3	0.809E+06	0.8440E-05	29.2	93.0	54.6
0.7225E-04	0.133E+07	1046.4	0.831E+06	0.8954E-05	29.7	90.6	52.0
0.7357E-04	0.133E+07	1065.4	0.852E+06	0.9514E-05	30.2	88.1	49.6
0.7488E-04	0.133E+07	1084.4	0.874E+06	0.1011E-04	30.7	85.7	47.3
0.7619E-04	0.133E+07	1103.4	0.894E+06	0.1073E-04	31.3	83.2	45.2
0.7751E-04	0.133E+07	1122.5	0.914E+06	0.1139E-04	31.8	80.8	43.2
0.7882E-04	0.133E+07	1141.5	0.934E+06	0.1206E-04	32.2	78.3	41.4
0.8013E-04	0.133E+07	1160.5	0.953E+06	0.1277E-04	32.7	75.9	39.8
0.8145E-04	0.133E+07	1179.5	0.972E+06	0.1351E-04	33.2	73.4	38.4
0.8276E-04	0.133E+07	1198.6	0.990E+06	0.1427E-04	33.7	71.0	37.3
0.8408E-04	0.133E+07	1217.6	0.101E+07	0.1507E-04	34.2	68.5	36.5
0.8539E-04	0.134E+07	1236.6	0.102E+07	0.1588E-04	34.7	66.1	35.8
0.8670E-04	0.134E+07	1255.7	0.104E+07	0.1674E-04	35.1	63.6	35.1
0.8802E-04	0.134E+07	1274.7	0.106E+07	0.1763E-04	35.6	61.2	34.4
0.8933E-04	0.134E+07	1293.7	0.107E+07	0.1853E-04	36.0	58.7	33.7
0.9064E-04	0.134E+07	1312.7	0.109E+07	0.1948E-04	36.5	56.3	32.9
0.9196E-04	0.134E+07	1331.8	0.110E+07	0.2048E-04	36.9	53.8	32.2
0.9327E-04	0.134E+07	1350.8	0.112E+07	0.2150E-04	37.4	51.4	31.5

0.9459E-04	0.134E+07	1369.8	0.113E+07	0.2255E-04	37.8	48.9	30.8
0.9590E-04	0.134E+07	1388.8	0.115E+07	0.2363E-04	38.2	46.5	30.1
0.9721E-04	0.134E+07	1407.9	0.116E+07	0.2476E-04	38.6	44.0	29.3
0.9853E-04	0.134E+07	1426.9	0.117E+07	0.2593E-04	39.0	41.6	28.6
0.9984E-04	0.134E+07	1445.9	0.118E+07	0.2712E-04	39.4	39.2	27.9
0.1012E-03	0.134E+07	1464.9	0.119E+07	0.2835E-04	39.8	36.7	27.2
0.1025E-03	0.134E+07	1484.0	0.120E+07	0.2961E-04	40.1	34.3	26.5
0.1038E-03	0.134E+07	1503.0	0.122E+07	0.3091E-04	40.5	31.8	25.7
0.1051E-03	0.134E+07	1522.0	0.122E+07	0.3223E-04	40.9	29.4	25.0
0.1064E-03	0.134E+07	1541.0	0.123E+07	0.3357E-04	41.2	26.9	24.3
0.1077E-03	0.134E+07	1560.1	0.124E+07	0.3494E-04	41.5	24.5	23.6
0.1090E-03	0.134E+07	1579.1	0.125E+07	0.3632E-04	41.8	22.0	22.8
0.1103E-03	0.134E+07	1598.1	0.126E+07	0.3772E-04	42.1	19.6	22.1
0.1117E-03	0.134E+07	1617.1	0.127E+07	0.3910E-04	42.4	17.1	21.4
0.1130E-03	0.134E+07	1636.2	0.127E+07	0.4051E-04	42.7	14.7	20.7
0.1143E-03	0.134E+07	1655.2	0.128E+07	0.4186E-04	42.9	12.2	20.0
0.1156E-03	0.134E+07	1674.2	0.129E+07	0.4324E-04	43.2	9.8	19.2
0.1169E-03	0.134E+07	1693.2	0.129E+07	0.4452E-04	43.4	7.3	18.5
0.1182E-03	0.134E+07	1712.3	0.130E+07	0.4581E-04	43.6	4.9	17.8
0.1195E-03	0.134E+07	1731.3	0.130E+07	0.4760E-04	43.8	12.1	19.9
0.1209E-03	0.134E+07	1750.3	0.131E+07	0.4960E-04	44.0	11.0	19.6
0.1222E-03	0.134E+07	1769.3	0.131E+07	0.5201E-04	44.1	9.9	19.3
0.1235E-03	0.134E+07	1788.4	0.131E+07	0.5418E-04	44.3	8.7	18.9
0.1248E-03	0.134E+07	1807.4	0.132E+07	0.5626E-04	44.4	7.6	18.6
0.1261E-03	0.134E+07	1826.4	0.132E+07	0.5810E-04	44.5	6.5	18.3
0.1274E-03	0.134E+07	1845.4	0.132E+07	0.5961E-04	44.6	5.3	17.9
0.1287E-03	0.134E+07	1864.5	0.132E+07	0.6080E-04	44.6	4.2	17.6
0.1301E-03	0.134E+07	1883.5	0.132E+07	0.6160E-04	44.6	1.7	16.9
0.1314E-03	0.134E+07	1902.5	0.132E+07	0.6188E-04	44.7	0.6	16.5
						0.0	16.4

D.5. FORTRAN source code for JOIST program.

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C *****
C * Joist - Simulation of structural behavior of LSF floors in standard *
C * fire resistance tests. *
C * (Simulation of structural behavior of uniformly loaded *
C * lipped-C-section joists subjected to severe heating) *
C *
C * Assumptions: *
C * * LSF floor is modelled by a single simply-supported joist with *
C * initial imperfection (due to thermal bowing) subjected to *
C * uniformly-distributed vertical tributary load. *
C * * Sub-floor and gypsum board do not carry any loads. *
C * * Flexural-torsional and weak axis buckling failure modes are *
C * prevented by adequate lateral restraints. *
C * * Steel stress-strain relationships at elevated temperatures are *
C * linear up to the yield strength. *
C * * The joist ends are hinged (and not restrained against horizontal *
C * restraints. *
C * * There is no temperature variation in the horizontal direction *
C * along the joist. However, the temperature varies across the *
C * joist section from the hot (bottom) to the cold (top) flange. *
C * * The initial imperfection (thermal bowing) consists of stress- *
C * free bowing (based on the assumption of linear gradient of *
C * thermal elongation strain across the joist section), reduced by *
C * reduction coefficient RCLD<1. This reduction in thermal bowing *
C * (caused by the actual non-linearity of thermal strain gradient) *
C * curvature translates into an internal structural strains and *
C * stress, that are modelled as resulting from prestress moment EM, *
C * which has an unloading effect. If the user expects the gradient *

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C      *      of thermal strains to be linear, use RCLD=1 (the program will
C      *      compute EM=0. in this case).
C      *
C      *
C      * At each time step (hot/cold flange temperature combination), the
C      * program evaluates the deflected shape of the joist, and checks the
C      * mid-span section for the action of the bending moment (about the
C      * strong axis) due to the vertical load. Any axial load (due to
C      * translational end restraint) is neglected.
C      *
C      * The final output for every time step is the failure criterion CRIT,
C      * which is the ratio of the midspan moment to the moment capacity
C      * The section is considered to fail at the time when failure criterion
C      * exceeds unity. This time is indicative of the fire resistance of the
C      * LSF floor.
C      *
C      * The program applies to lipped-C-section joists only. Routines can be
C      * added for other types of sections, if their structural behavior, when
C      * subjected to severe heating, is known to be similar.
C      *
C      * Width of compression elements in effective joist cross-sections is
C      * determined in accordance with Clause 5.6.2 of S136-94, to account for
C      * local buckling effects. Effective cross-section dimensions are assumed
C      * to be insensitive to temperature (i.e. based on steel properties at
C      * room temperature, and compressive stress  $f=F_y$ ). See Subroutine CSECT.
C      *
C      * Modulus-weighted (temperature-dependent) section properties are
C      * computed at every time step for 4 types of sections: unreduced,
C      * in compression, in bending with hot flange compressed, in bending with
C      * cold flange compressed. See Subroutine GEOM.
C      *
C      * Three models for steel thermal elongation strain implemented (see
C      * Subroutine BOW). Three models for steel modulus of elasticity
C      * retention factor implemented (see Subroutine ELST and associated
C      * functions). Three models for steel yield strength retention factor
C      * implemented (see Subroutine YIELD and associated functions). Other
C      * models, associated with steel properties at elevated temperatures,
C      * can be added to these subroutines (if known from experiments, or for
C      * parametric studies).
C      *
C      * Creep/Stress Relaxation procedure implemented. Joist deflections
C      * cannot be less than in the previous time step.
C      *
C      *
C      * BY FARID ALFAWAKHIRI - LAST REVISED ON December 18, 2000
C      * .....
C
C      IMPLICIT REAL*8 (A-H,O-Z)
C      CHARACTER INPUT*80, OUTPUT*80
C      COMMON/SET1/ TSi(1000), TH(1000), TC(1000)
C      COMMON/SET2/ AE1(100), Io1(100), YE1(100), E1(100)
C      COMMON/SET3/ AE2(100), Io2(100), YE2(100), E2(100)
C      COMMON/SET4/ AE3(100), Io3(100), YE3(100), E3(100)
C      COMMON/SET5/ AE4(100), Io4(100), YE4(100), E4(100), FY4(100), FS4(100)
C      COMMON/SET7/ T1(100), T2(100), T3(100), T4(100)
C      COMMON/SET8/ FIM(100), RMF(100), YN(100)
C      COMMON/SET9/ z(101), BMz(101), FIZ(101), ACURV(100), SLP(101), DFL(101)
C      COMMON/SET11/ PRNT1(101), PRNT2(101), PRNT3(101), PRNT4(101)
C      COMMON/SET12/ PRNT5(101), PRNT6(101), PRNT7(102), PRNT8(102)
C
C      Specify input and output files
C
C      WRITE (*,1000)
1000 FORMAT (2X,'Program JOIST - fire resistance of LSF floors'/)
C      WRITE (*,1001)
1001 FORMAT (2X,'ENTER THE NAME OF THE INPUT FILE:',$)
C      READ (*,1003) INPUT

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        WRITE (*,1002)
1002  FORMAT (2X,'ENTER THE NAME OF THE OUTPUT FILE:',$,)
        READ (*,1003) OUTPUT
1003  FORMAT (1A80)
C
C      Open input and output files
C
        CLOSE (9)
        CLOSE (7)
        OPEN (9,FILE=INPUT,STATUS='OLD')
        OPEN (7,FILE=OUTPUT,STATUS='NEW')
C
C      Read the input file
C
        CALL DATIN (Ao, Bo, Co, ts, Ro, Ap, H,
1          E, IEt, Fy, IFyt, Iext, P, RCLD, NTS, z1, PRNT)
C
C      Discretize joist section and reduced sections (in compression and bending)
C      Currently each section is divided to 100 elements
C
        CALL CSECT (Ao, Bo, Co, ts, Ro, Ap, Fy, E)
C
C      Set up initial parameters
C      Calculate section geometry properties at room temperatures
C
        EH=1.
        EC=1.
        DO 11 I=1,100
        E1(I)=1.
        E2(I)=1.
        E3(I)=1.
        E4(I)=1.
11  CONTINUE
C
        CALL GEOM (Ao,CG1,CG3,CG4,WI1,A2,S3c,S3t,S4c,S4t,WI3,WI4)
        BI=WI1
C      TSo=-1
C      Ta=0.0
C      Td=0.0
C      Fyh=Fy
C      Fyc=Fy
C      CHCK=1.
C      Dthc=0.
C      Dcor=0.
C      D1c=0.
C      D2c=0.
C
C      Compute bending moments and deflections due to tributary load
C      STMM = bending moment at midspan due to tributary load
C      STM1 = bending moment at distance z1 (from left support) due to tr.load
C      Dsto = initial midspan deflection due tributary vertical load (room temp.)
C      Dsto1= initial deflection at z1 due to tributary load (at room temp.)
C
        STMM=P*H*H/8.
        STM1=0.5*P*z1*(H-z1)
        Dsto=5.*P*(H**4.)/(384.*E*BI)
        Dsto1=P*z1*(H*H*H-2.*H*z1*z1+z1*z1*z1)/(24.*E*BI)
        WRITE (*,1005) CG1,WI1,Dsto,STMM
1005  FORMAT (5X,4E14.5)
C
C
C
        WRITE (7, 1008)
1008  FORMAT (3X,'TSi',4X,'Ta',5X,'Td',3X,'DRth',4X,'Dst',
1          4X,' D ',3X,'Dcor',7X,'RM',5X,'CRIT',5X,'D1c')
C
C      Generate array of distances z from left support to midspan at equal
C      increments of dH.

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```

C      Do repeated operations at every time (temperature combination) step
C
      z(1)=0.
      dH=H/200.
      DO 21 I=2,101
      z(I)=z(I-1)+dH
21 CONTINUE
      DMAX1=0.
      DMAX2=0.
      DMAX3=0.
      DO 101 IT=1,NTS

C
C      Compute average temperature Ta of the joist, and the temperature difference
C      Td between the hot flange and the cold flange
C
      Tmax=TH(IT)
      Tmin=TC(IT)
      Ta=(Tmax+Tmin)/2.
      Td=Tmax-Tmin
      IF (Td. LT. 0.) Td=0.

C
C      Compute the thermal expansion stains at extreme hot and cold fibres,
C      then the assumed stress-free thermal bowing curvature FI, the stress-free
C      imperfection (due to thermal bowing) Dth at midspan and Dth1 at z1
C      Dthc = corrected Dth, which is not less than Dth in previous time step
C
C      Compute the reduced mid-span deflection DRth (due to thermal bowing).
C      This reduction in thermal bowing is due to non-linearity of thermal
C      gradient across the joist section.
C      DRth1= Dth1 reduced by RCLD (due to nonlinear thermal strain gradients)
C
      CALL BOW (Ao,Tmax,Tmin,Iext,FI)
      Dth=FI*H*H/8.
      Dth1=0.5*FI*z1*(H-z1)
      Dthc=Dth
      IF (Dthc. LT. DMAX1) Dthc=DMAX1
      IF (Dthc. GE. DMAX1) DMAX1=Dthc
      DRth=RCLD*Dth
      DRthc=RCLD*Dthc
      DRth1=RCLD*Dth1

C
C      Compute modulus of elasticity retention factors for each discretized
C      section element and section extreme fibres
C      GRAD = temperature gradient (linear) across steel section, deg.C/mm
C      EH = modulus of elasticity retention factor at extreme hot fibre
C      EC = modulus of elasticity retention factor at extreme cold fibre
C      E1, E2, E3, E4 are modulus retention factors for section elements
C
      GRAD=Td/Ao
      CALL ELAST (IET,Tmax,Tmin,GRAD,EH,EC)

C
C      Compute modulus weighted section properties
C
      CALL GEOM (Ao,CG1,CG3,CG4,WI1,A2,S3c,S3t,S4c,S4t,WI3,WI4)
      Ea=(1.-3.E-4*Ta+3.7E-7*Ta**2-6.1E-9*Ta**3+5.4E-12*Ta**4)
      CHCK=WI1/(Ea*BI)

C
C      Compute the temperature dependent yield strength in section elements and
C      the extreme fibres of hot and cold flanges
C
      CALL YIELD (Fy,IFyt,Tmax,Tmin,Fyh,Fyc)

C
C      Find the moment resistance RM of the joist section based on inelastic
C      capacity, where tensile strains are not limited, but the compressive
C      strains are limited to the yield strain (cold flange compressed).
C      eclmt = limiting compressive strain at extreme cold flange fibre
C      TOL = tolerance for equilibrium of internal forces Q
C

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```

      eclmt=Fyc/(EC*E)
      Blmt=0.
      Tlmt=Ao
      TOL=Fyh*A2/10000.
C
C      Start iteration to find the location of neutral axis
C      YNRM = distance of newtral axis from the hot (bottom) flange outer face
C      FIRM = curvature corresponding to RM
C      Note that distance from centroid of element to hot face is YE3(101-I)
C
      DO 141 ITER=1,50
      YNRM=(Blmt+Tlmt)/2.
      FIRM=eclmt/(Ao-YNRM)
      Q=0.
      DO 142 I=1,100
      FS4(I)=(YNRM-YE3(101-I))*FIRM*E4(I)*E
      IF (FS4(I).GT.Fy4(I)) FS4(I)=Fy4(I)
      IF (FS4(I).LT.-Fy4(I)) FS4(I)=-Fy4(I)
      Q=Q+AE4(I)*FS4(I)
142 CONTINUE
      IF (Q.LT.0.) BLMT=YNRM
      IF (Q.GT.0.) TLMT=YNRM
      IF (Q.LT.0.) Q=-Q
      IF (Q.LT.TOL) GO TO 145
141 CONTINUE
      WRITE(*,1020)
1020 FORMAT (2X,'CONVERGENCE NOT ACHIEVED FOR YNRM')
      GO TO 199
145 RM=0.0
      DO 147 I=1,100
      RM=RM+AE4(I)*FS4(I)*(YNRM-YE3(101-I))
147 CONTINUE
C
C      Find the moment-curvature relationship for curvature range of 3 FIRM
C      FIM = curvature
C      RMF = resisted moment corresponding to curvature FIM
C      YN = location of neutral axis (from bottom flange outer face)
C
      FSTEP=3.*FIRM/100.
      DO 151 N=1,100
      RealN=N
      FIM(N)=FSTEP*RealN
      Blmt=0.
      Tlmt=Ao
      TOL=Fyh*A2/10000.
      DO 152 ITER=1,50
      YN(N)=(Blmt+Tlmt)/2.
      Q=0.
      DO 153 I=1,100
      FS4(I)=(YN(N)-YE3(101-I))*FIM(N)*E4(I)*E
      IF (FS4(I).GT.Fy4(I)) FS4(I)=Fy4(I)
      IF (FS4(I).LT.-Fy4(I)) FS4(I)=-Fy4(I)
      Q=Q+AE4(I)*FS4(I)
153 CONTINUE
      IF (Q.LT.0.) BLMT=YN(N)
      IF (Q.GT.0.) TLMT=YN(N)
      IF (Q.LT.0.) Q=-Q
      IF (Q.LT.TOL) GO TO 154
152 CONTINUE
      WRITE(*,1021)
1021 FORMAT (2X,'CONVERGENCE NOT ACHIEVED FOR YN(N)')
      GO TO 199
154 RMF(N)=0.0
      DO 155 I=1,100
      RMF(N)=RMF(N)+AE4(I)*FS4(I)*(YN(N)-YE3(101-I))
155 CONTINUE
151 CONTINUE
      IF (TSi(IT).NE.45.) GO TO 157

```

```

c      DO 158 I=1,100
c      write (*,*) FIM(I), RMF(I), YN(I)
c 158 continue
157 continue
C
C      Compute the end moments EM (due to nonlinear thermal strain gradients)
C      Compute the total moment BM at midspan
C      Compute the total moment BM1 at distance z1 from left support
C      Compute the failure criterion CRIT
C      Compute midspan deflection Dst due to deterioration of stiffness
C      Compute deflection Dst1 (at z1) due to deterioration of stiffness
C      Compute total midspan deflection D
C      Compute total deflection Dz1 (at z1)
C      When Td decreases with time, D is forced not to decrease.
C      Dcor = corrected D, which is not less than D in previous time step
C      D1c = corrected Dz1, which is not less than Dz1 in previous time step
C
      EM=(1.-RCLD)*FI*(E*WI1)
      BM=STMM-EM
      BM1=STM1-EM
      CRIT=BM/RM
      BMz(1)=-EM
      FIZ(1)=-(1-RCLD)*FI
      SLOPE=0.
      DO 171 I=2,101
      BMz(I)=0.5*P*z(I)*(H-z(I))-EM
      IF (BMz(I).GT.0.) GO TO 172
      FIZ(I)=BMz(I)/(E*WI1)
      GO TO 177
172 IF (BMz(I).GT.RMF(1)) GO TO 173
      FIZ(I)=BMz(I)*FIM(1)/RMF(1)
      GO TO 177
173 DO 175 J=2,100
      IF (RMF(J).LT.BMz(I)) GO TO 174
      FIZ(I)=FIM(J-1)+(BMz(I)-RMF(J-1))*FSTEP/(RMF(J)-RMF(J-1))
      GO TO 177
174 CONTINUE
175 CONTINUE
      FIZ(I)=FIM(100)+(BMz(I)-RMF(100))*FSTEP/(RMF(100)-RMF(99))
177 CONTINUE
      ACURV(I-1)=(FIZ(I-1)+FIZ(I))*dH/2.
      SLOPE=SLOPE+ACURV(I-1)
171 CONTINUE
C
      DFL(1)=0.
      SLP(1)=SLOPE
      DFL(2)=(SLOPE-0.5*ACURV(1))*dH
      SLP(2)=SLP(1)-ACURV(1)
      DO 178 I=3,101
      SLP(I)=SLP(I-1)-ACURV(I-1)
      DFL(I)=SLOPE*z(I)
      DO 180 J=1,(I-1)
      DFL(I)=DFL(I)-ACURV(J)*dH*(I-J-0.5)
180 CONTINUE
178 CONTINUE
C
      Dst=DFL(101)+(1.-RCLD)*Dth-Dsto
      D=DRth+Dst
      Dcor=D
      IF (Dcor. LT. DMAX2) Dcor=DMAX2
      IF (Dcor. GE. DMAX2) DMAX2=Dcor
C
      DO 181 I=1,101
      IF (z(I).LT.z1) GO TO 182
      Dst1=DFL(I-1)+(DFL(I)-DFL(I-1))*(z1-z(I-1))/dH
      GO TO 183
182 CONTINUE
181 CONTINUE

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183 Dst1=Dst1+(1.-RCLD)*Dth1-Dstol
    Dz1=DRth1+Dst1
    Dlc=Dz1
    IF (Dlc. LT. DMAX3) Dlc=DMAX3
    IF (Dlc. GE. DMAX3) DMAX3=Dlc
C
C      For user-specified time step PRNT save to memory the detailed information
C      about moment-curvature relationship, moment/curvature/deflection along
C      the joist, stresses at section z1
C      PRNT1 = curvature for moment-curvature relationship
C      PRNT2 = location of neutral axis (from bottom extreme fibre)
C              for curvature PRNT1
C      PRNT3 = resisting moment for curvature PRNT1
C      PRNT4 = total bending moment at distance z from left support
C      PRNT5 = curvature at distance z from left support
C      PRNT6 = deflection at distance z from left support
C      PRNT7 = distance from bottom extreme fibre
C      PRNT8 = stress at distance PRNT7 at section z1
C
    IF (TSi(IT).NE.PRNT) GO TO 107
    PRNT1(1)=0.
    PRNT2(1)=Ao/2.
    PRNT3(1)=0.
    PRNT4(1)=BMz(1)
    PRNT5(1)=Fiz(1)
    PRNT6(1)=DFL(1)
    DO 185 I=2,101
    PRNT1(I)=FIM(I-1)
    PRNT2(I)=YN(I-1)
    PRNT3(I)=RMF(I-1)
    PRNT4(I)=BMz(I)
    PRNT5(I)=Fiz(I)
    PRNT6(I)=DFL(I)
185 CONTINUE
C
    DO 187 I=1,101
    IF (z(I).LT.z1) GO TO 188
    Fiz1=Fiz(I-1)+(Fiz(I)-Fiz(I-1))*(z1-z(I-1))/dH
    GO TO 189
188 CONTINUE
187 CONTINUE
189 IF (Fiz1.GT.0.) GO TO 191
    YNz1=Ao-CG3
    PRNT7(1)=Ao
    PRNT7(102)=0.0
    PRNT8(1)=EC*(-BM1/S3t)
    PRNT8(102)=EH*(BM1/S3c)
    DO 190 I=1,100
    PRNT7(I+1)=YE4(101-I)
    PRNT8(I+1)=(YNz1-YE4(101-I))*Fiz1*E3(I)*E
190 CONTINUE
    GO TO 197
191 IF (Fiz1.GT.FIM(100)) GO TO 194
    DO 192 J=2,101
    IF (PRNT1(J).LT.Fiz1) GO TO 193
    YNz1=PRNT2(J-1)+(PRNT2(J)-PRNT2(J-1))*(Fiz1-PRNT1(J-1))/
1      (PRNT1(J)-PRNT1(J-1))
    PRNT7(1)=Ao
    PRNT7(102)=0.0
    PRNT8(1)=(YNz1-Ao)*Fiz1*EC*E
    IF (PRNT8(1).LT.-Fyc) PRNT8(1)=-Fyc
    PRNT8(102)=YNz1*Fiz1*EH*E
    IF (PRNT8(102).GT.Fyh) PRNT8(102)=Fyh
    DO 1193 I=1,100
    PRNT7(I+1)=YE3(101-I)
    PRNT8(I+1)=(YNz1-YE3(101-I))*Fiz1*E4(I)*E
    IF (PRNT8(I+1).GT.Fy4(I)) PRNT8(I+1)=Fy4(I)
    IF (PRNT8(I+1).LT.-Fy4(I)) PRNT8(I+1)=-Fy4(I)

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1193 CONTINUE
      GO TO 197
193 CONTINUE
192 CONTINUE
      GO TO 197
194 YNz1=YN(100)
      PRNT7(1)=Ao
      PRNT7(102)=0.0
      PRNT8(1)=-Fyc
      PRNT8(102)=Fyh
      DO 195 I=1,100
        PRNT7(I+1)=YE4(101-I)
        IF (PRNT7(I+1).GE.YNz1) PRNT8(I+1)=-FY4(I)
        IF (PRNT7(I+1).LT.YNz1) PRNT8(I+1)=FY4(I)
195 CONTINUE
197 CONTINUE
C
C
C      Write the results of the time step to the output file
C
      107 WRITE (7, 1007) TSi(IT),Ta,Td,DRth,Dst,D,Dcor,RM,CRIT,Dlc
1007 FORMAT (X,F5.1,2F7.1,F6.1,3F7.1,E12.3,F7.3,F7.1)
C
      101 CONTINUE
C
C
C      After completion of all time steps write the detailed output information
C      for step PRNT
C
      WRITE (7, 1051) PRNT
1051 FORMAT (/2X,'DETAILED DATA FOR TIME STEP',F5.1)
      WRITE (7, 1052)
1052 FORMAT (5X,'PRNT1',5X,'PRNT3',6X,'z',5X,'PRNT4',
1       7X,'PRNT5',5X,'PRNT6',2X,'PRNT7',2X,'PRNT8')
C
      DO 198 I=1,101
        WRITE (7,1053) PRNT1(I),PRNT3(I),z(I),PRNT4(I),PRNT5(I),
1       PRNT6(I),PRNT7(I),PRNT8(I)
1053 FORMAT (X,E10.4,E10.3,F7.1,E11.3,E12.4,F8.1,2F7.1)
      198 CONTINUE
      WRITE (7,1054) PRNT7(102),PRNT8(102)
1054 FORMAT (59X,2F7.1)
C
C
C      199 STOP
      END
C
C
C      *****
C      * DATIN *
C      * READS THE INPUT FILE
C      *
C      *****
C
      SUBROUTINE DATIN (Ao, Bo, Co, ts, Ro, Ap, H,
1       E, Iet, Fy, IFyt, Iext, P, RCLD, NTS, z1, PRNT)
C
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION TITLE(20)
      COMMON/SET1/ TSi(1000), TH(1000), TC(1000)
C
C      PROBLEM IDENTIFICATION
C
      READ (9,2001) TITLE
2001 FORMAT (20A4)
      WRITE (7,2002) TITLE
2002 FORMAT (1H1/,2X,20A4)
C
C      READ geometry parameters (for lipped-C-section)

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C      Ao = out to out depth of joist section
C      Bo = out to out width of flange
C      Co = out to out width of lip stiffener
C      ts = black metal thickness
C      Ro = inside bend radius (not more than 4ts)
C      Ap = width of web perforation
C      H  = span length
C
C      READ (9,*) Ao, Bo, Co, ts, Ro, Ap, H
C
C      READ steel sheet properties
C      E  = modulus of elasticity of steel at room temperature
C      IET = indicator for the formulation of the modulus of elasticity
C           retention factor at elevated temperatures
C           1 for Gerlich (1995) formula, extended to 1000 degrees C
C           2 for Makelainen and Miller (1983) formula for steady-state tests
C           3 for Makelainen and Miller (1983) formula for transient tests
C      Fy = yield strength of steel
C      IFyt= indicator for the formulation of the yield strength retention
C           factor at elevated temperatures
C           1 for Gerlich (1995) formula, extended to 1000 degrees C
C           2 for Makelainen and Miller (1983) formula, extended to 1000 deg.C
C           3 for BS 5950: Part 8 formula, extended to 1000 deg. C
C      Iext= indicator for the formulation of steel thermal elongation strain
C           1 for Lie (1992) formula
C           2 for Lawson and Newman (1990) formula
C           3 for Makelainen and Miller (1983) formula
C
C      READ (9,*) E, IET, Fy, IFyt, Iext
C
C      P  = tributary vertical load per unit length of joist
C      RCLD= reduction coefficient for thermal bowing deflection, which depends
C           on rotational restraints at joist ends and internal stresses caused
C           by non-uniform heating
C      NTS = number of time steps (hot/cold flange temperature combinations),
C           current dimension of the program limits NTS to 1000
C      z1  = distance from left support of section for deflection output
C      PRNT= time step (TSi) for which detailed information output desired,
C           enter negative value if no detailed info needed
C
C      READ (9,*) P, RCLD, NTS, z1, PRNT
C      H2=H/2.
C      IF (z1.GT.H2) z1=H-z1
C
C      READ for every time step:
C      TSi = time, or time step number (combination identification number)
C      TH  = hot flange temperature
C      TC  = cold flange temperature
C      (Note: currently number of TS, TH and TC is limited by 1000)
C      and close the input file
C
C      DO 201 I=1,NTS
C      READ (9,*) TSi(I), TH(I), TC(I)
201 CONTINUE
C
C      CLOSE (9)
C
C      RETURN
C      END
C
C      *****
C      * CSECT *
C      * DISCRETIZES LIPPED-C-SECTION *
C      * (SINGLY SYMMETRIC) *
C      *****

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C      SUBROUTINE CSECT (Ao, Bo, Co, ts, Ro, Ap, Fy, E)
C
C      IMPLICIT REAL*8 (A-H,O-Z)
COMMON/SET2/ AE1(100), Io1(100), YE1(100), E1(100)
COMMON/SET3/ AE2(100), Io2(100), YE2(100), E2(100)
COMMON/SET4/ AE3(100), Io3(100), YE3(100), E3(100)
COMMON/SET5/ AE4(100), Io4(100), YE4(100), E4(100), FY4(100)
C
C      Compute geometry of flat elements
C      r = mid-thickness bend radius
C      A = web flat width
C      B = flange flat width
C      C = lip flat width
C
C      r=Ro+0.5*ts
C      A=Ao-ts-2.*r
C      B=Bo-ts-2.*r
C      C=Co-ts-Ro
C
C      Discretize the unreduced unperforated section to 100 elements
C      Elements 1 and 100 are flanges
C      Elements 2 and 99 are bent parts of section
C      Elements 3-10 and 91-98 are lips
C      Elements 11-50 and 51-90 are web
C      AE1 = area of discretization element
C      Io1 = moment of inertia of element about an axis, parallel to the axis
C      of symmetry of the section, passing through the centroid of element
C      YE1 = distance from centroid of element to the outside face of cold flange
C
C      AE1(1)=B*ts
C      Io1(1)=AE1(1)*ts*ts/12.
C      YE1(1)=0.5*ts
C
C      AE1(2)=3.1416*ts*r
C      Io1(2)=0.29845*r*r*r*ts
C      YE1(2)=0.5*ts+0.3634*r
C
C      AE1(3)=C*ts/8.
C      Io1(3)=AE1(3)*C*C/768.
C      YE1(3)=0.5*ts+r+C/16.
C      DO 301 I=4,10
C      AE1(I)=AE1(3)
C      Io1(I)=Io1(3)
C      YE1(I)=YE1(I-1)+C/8.
301 CONTINUE
C
C      AE1(11)=A*ts/80.
C      Io1(11)=AE1(11)*A*A/76800.
C      YE1(11)=0.5*ts+r+A/160.
C      DO 302 I=12,50
C      AE1(I)=AE1(11)
C      Io1(I)=Io1(11)
C      YE1(I)=YE1(I-1)+A/80.
302 CONTINUE
C
C      DO 303 I=51,100
C      AE1(I)=AE1(101-I)
C      Io1(I)=Io1(101-I)
C      YE1(I)=Ao-YE1(101-I)
303 CONTINUE
C
C      Calculate the reduced width of lip stiffener (for f=Fy) according to
C      clause 5.6.2.7 of S136-94
C      Cef = effective width of lip stiffener
C      WB = flat width ratio
C      LIM1 and LIM2 = limiting flat width ratios
C

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WB=C/ts
LIM1=0.644*DSQRT(0.43*E/Fy)
IF (WB. GT. LIM1) GO TO 312
Cef=C
GO TO 311
312 Cef=ts*1.475*LIM1*(1.-0.323*LIM1/WB)
311 CONTINUE
C
C      Calculate the reduced width of flange in compression (for f=Fy) according
C      to clause 5.6.2.3 of S136-94
C      Bef = effective width of flange
C      Dummy parameters DUM1, DUM2, DUM3, ks
C
      LIM2=0.644*DSQRT(4.0*E/Fy)
      WB=B/ts
      DUM1=Co/B
      IF (WB. GT. LIM1) GO TO 322
      Bef=B
      GO TO 320
C
322 IF (WB. GT. LIM2) GO TO 327
      DUM2=((C/(ts*(WB/LIM2-0.327)))**3.)/4788.
      IF (DUM2. LT. 1.) Cef=Cef*DUM2
      IF (DUM1. GT. 0.25) GO TO 323
      IF (DUM2. GE. 1.) ks=4.
      IF (DUM2. LT. 1.) ks=3.57*DSQRT(DUM2)+0.43
      GO TO 321
323 IF (DUM2. GE. 1.) ks=5.25-5.*DUM1
      IF (DUM2. LT. 1.) ks=(4.82-5.*DUM1)*DSQRT(DUM2)+0.43
      GO TO 321
C
327 DUM2=((C/ts)**3.)/12./((115.*WB/LIM2+5.))
      IF (DUM2. LT. 1.) Cef=Cef*DUM2
      IF (DUM1. GT. 0.25) GO TO 328
      IF (DUM2. GE. 1.) ks=4.
      IF (DUM2. LT. 1.) ks=3.57*(DUM2**0.333)+0.43
      GO TO 321
328 IF (DUM2. GE. 1.) ks=5.25-5.*DUM1
      IF (DUM2. LT. 1.) ks=(4.82-5.*DUM1)*(DUM2**0.333)+0.43
C
321 CONTINUE
      DUM3=DSQRT(ks*E/Fy)
      Bef=ts*0.95*DUM3*(1.-0.208*DUM3/WB)
      IF (Bef.GT.B) Bef=B
320 CONTINUE
C
C      Calculate the reduced width of web (for f=Fy) according to
C      clause 5.6.2.2 of S136-94
C      Aef = effective width of web
C      Aef2= effective width of half web
C
      WB=A/ts
      IF (WB. LE. LIM2) Aef=A
      IF (WB. GT. LIM2) Aef=1.475*LIM2*(1.-0.323*LIM2/WB)
      Aef2=Aef/2.
C
C      If the critical sections to check are perforated sections (Ap>0)
C      the web is considered to consist of 2 unstiffened elements, according to
C      clause 6.8.1 of S136-94, with the width of each unstiffened element
C      determined according to clause 5.6.2.7 of S136-94
C
      IF (Ap. LE. 0.) GO TO 331
      DUM1=0.5*(A-Ap)
      WB=DUM1/ts
      IF (WB. LE. LIM1) DUM2=DUM1
      IF (WB. GT. LIM1) DUM2=ts*1.475*LIM1*(1.-0.323*LIM1/WB)
      IF (DUM2. LT. Aef2) Aef2=DUM2
331 CONTINUE

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C
C      Discretize the reduced section FOR COMPRESSION to 100 elements
C      Elements 1 and 100 are flanges
C      Elements 2 and 99 are bent parts of section
C      Elements 3-10 and 91-98 are lips
C      Elements 11-50 and 51-90 are web
C      AE2 = area of discretization element
C      Io2 = moment of inertia of element about an axis, parallel to the axis
C            of symmetry of the section, passing through the centroid of element
C      YE2 = distance from centroid of element to the outside face of cold flange
C
      AE2(1)=Bef*ts
      Io2(1)=AE2(1)*ts*ts/12.
      YE2(1)=YE1(1)
C
      AE2(2)=AE1(2)
      Io2(2)=Io1(2)
      YE2(2)=YE1(2)
C
      AE2(3)=Cef*ts/8.
      Io2(3)=AE2(3)*Cef*Cef/768.
      YE2(3)=0.5*ts+r+Cef/16.
      DO 341 I=4,10
      AE2(I)=AE2(3)
      Io2(I)=Io2(3)
      YE2(I)=YE2(I-1)+Cef/8.
341 CONTINUE
C
      AE2(11)=Aef2*ts/40.
      Io2(11)=AE2(11)*Aef2*Aef2/19200.
      YE2(11)=0.5*ts+r+Aef2/80.
      DO 342 I=12,50
      AE2(I)=AE2(11)
      Io2(I)=Io2(11)
      YE2(I)=YE2(I-1)+Aef2/40.
342 CONTINUE
C
      DO 343 I=51,100
      AE2(I)=AE2(101-I)
      Io2(I)=Io2(101-I)
      YE2(I)=Ao-YE2(101-I)
343 CONTINUE
C
C      Discretize the reduced section FOR BENDING (HOT FLANGE COMPRESSED)
C      Elements 1 and 100 are flanges
C      Elements 2 and 99 are bent parts of section
C      Elements 3-10 and 91-98 are lips
C      Elements 11-50 and 51-90 are web
C      AE3 = area of discretization element
C      Io3 = moment of inertia of element about an axis, parallel to the axis
C            of symmetry of the section, passing through the centroid of element
C      YE3 = distance from centroid of element to the outside face of cold flange
C
      DO 351 I=1,10
      AE3(I)=AE1(I)
      Io3(I)=Io1(I)
      YE3(I)=YE1(I)
351 CONTINUE
C
      IF (Ap. LE. 0.) GO TO 354
      Aef2=0.5*(A-Ap)
      AE3(11)=Aef2*ts/40.
      Io3(11)=AE3(11)*Aef2*Aef2/19200.
      YE3(11)=0.5*ts+r+Aef2/80.
      DO 352 I=12,50
      AE3(I)=AE3(11)
      Io3(I)=Io3(11)
      YE3(I)=YE3(I-1)+Aef2/40.

```

```

352 CONTINUE
C
    DO 353 I=51,90
        AE3(I)=AE3(101-I)
        Io3(I)=Io3(101-I)
        YE3(I)=Ao-YE3(101-I)
353 CONTINUE
    GO TO 357
C
354 DO 355 I=11,90
    AE3(I)=AE1(I)
    Io3(I)=Io1(I)
    YE3(I)=YE1(I)
355 CONTINUE
C
357 DO 358 I=91,100
    AE3(I)=AE2(I)
    Io3(I)=Io2(I)
    YE3(I)=YE2(I)
358 CONTINUE

C
C      Discretize the reduced section FOR BENDING (COLD FLANGE COMPRESSED)
C      Elements 1 and 100 are flanges
C      Elements 2 and 99 are bent parts of section
C      Elements 3-10 and 91-98 are lips
C      Elements 11-50 and 51-90 are web
C      AE4 = area of discretization element
C      Io4 = moment of inertia of element about an axis, parallel to the axis
C            of symmetry of the section, passing through the centroid of element
C      YE4 = distance from centroid of element to the outside face of cold flange
C      Note that distance from centroid of element to hot face is YE3(101-I)
C
    DO 371 I=1,100
        AE4(I)=AE3(101-I)
        Io4(I)=Io3(101-I)
        YE4(I)=Ao-YE3(101-I)
371 CONTINUE
C
C      RETURN
C      END

C
C      *****
C      * BOW *
C      * COMPUTES CURVATURE DUE TO
C      * THERMAL BOWING
C      *****
C
C      SUBROUTINE BOW (Ao,TH,TC,Iext,FI)
C
C      IMPLICIT REAL*8 (A-H,O-Z)
C
C      Compute thermal strains in hot and cold flanges, depending on the adopted
C      model for the formulation of steel thermal elongation strain
C      TH = hot flange temperature, degrees C
C      TC = cold flange temperature, degrees C
C      STH = thermal elongation strain in hot flange
C      STC = thermal elongation strain in cold flange
C      Iext = 1 for Lie (1992) formula
C            = 2 for Lawson and Newman (1990) formula
C            = 3 for Makelainen and Miller (1983) formula
C
401 IF (Iext. NE. 1) GO TO 402
    STH=0.000000002*TH*TH+0.000012*TH-0.0002408
    STC=0.000000002*TC*TC+0.000012*TC-0.0002408
    GO TO 499

```

```

C
402  IF (Iext. NE. 2) GO TO 403
      STH=0.000000004*TH*TH+0.000012*TH-0.0002416
      STC=0.000000004*TC*TC+0.000012*TC-0.0002416
      GO TO 499
C
403  IF (Iext. NE. 3) GO TO 498
      IF (TH. LE. 200.) STH=0.00000472*TH-0.0000944
      IF (TH. GT. 200.) STH=0.000000005*TH*TH+0.000008*TH-0.00095
      IF (TH. LE. 500.) STH=0.000000020*TH*TH-0.000007*TH+0.0028
      IF (TH. LE. 200.) STC=0.00000472*TC-0.0000944
      IF (TC. GT. 200.) STC=0.000000005*TC*TC+0.000008*TC-0.00095
      IF (TC. LE. 500.) STC=0.000000020*TC*TC-0.000007*TC+0.0028
      GO TO 499
C
498  WRITE (*,4001) Iext
4001  FORMAT (5X,'UNKNOWN MODEL',I3,2X,'FOR THERMAL ELONGATION')
      STOP
C
499  FI=(STH-STC)/Ao
      IF (FI. LT. 0.) FI=0.
C
C
      RETURN
      END
C
C
C *****
C * ELAST *
C * COMPUTES STEEL MODULUS OF
C * ELASTICITY RETENTION FACTOR
C * FOR EACH SECTION ELEMENT
C *****
C
      SUBROUTINE ELAST (Iet,TH,TC,GRAD,EH,EC)
C
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON/SET2/ AE1(100), Io1(100), YE1(100), E1(100)
      COMMON/SET3/ AE2(100), Io2(100), YE2(100), E2(100)
      COMMON/SET4/ AE3(100), Io3(100), YE3(100), E3(100)
      COMMON/SET5/ AE4(100), Io4(100), YE4(100), E4(100), FY4(100)
      COMMON/SET7/ T1(100), T2(100), T3(100), T4(100)
C
      TH  = hot flange temperature, degrees C
      TC  = cold flange temperature, degrees C
      GRAD = temperature gradient (linear) across steel section, deg.C/u.depth
      EH   = modulus of elasticity retention factor at extreme hot fibre
      EC   = modulus of elasticity retention factor at extreme cold fibre
      T1, T2, T3, T4 are temperatures of section elements
      E1, E2, E3, E4 are modulus retention factors for section elements
      Iet = indicator for the formulation of the modulus of elasticity
           retention factor at elevated temperatures
           1 for Gerlich (1995) formula, extended to 1000 degrees C
           2 for Makelainen and Miller (1983) formula for steady-state tests
           3 for Makelainen and Miller (1983) formula for transient tests
C
      Calculate temperatures for each discretized section element
C
      DO 501 I=1,100
      T1(I)=TC+GRAD*YE1(I)
      T2(I)=TC+GRAD*YE2(I)
      T3(I)=TC+GRAD*YE3(I)
      T4(I)=TC+GRAD*YE4(I)
501  CONTINUE
C
      Compute modulus retention factor for each section element
C

```

```

      IF (IET. NE. 1) GO TO 520
      EH=ELST1 (TH)
      EC=ELST1 (TC)
      DO 511 I=1,100
      E1 (I)=ELST1 (T1 (I))
      E2 (I)=ELST1 (T2 (I))
      E3 (I)=ELST1 (T3 (I))
      E4 (I)=ELST1 (T4 (I))
511  CONTINUE
      GO TO 599
C
520  IF (IET. NE. 2) GO TO 530
      EH=ELST2 (TH)
      EC=ELST2 (TC)
      DO 521 I=1,100
      E1 (I)=ELST2 (T1 (I))
      E2 (I)=ELST2 (T2 (I))
      E3 (I)=ELST2 (T3 (I))
      E4 (I)=ELST2 (T4 (I))
521  CONTINUE
      GO TO 599
C
530  IF (IET. NE. 3) GO TO 598
      EH=ELST3 (TH)
      EC=ELST3 (TC)
      DO 531 I=1,100
      E1 (I)=ELST3 (T1 (I))
      E2 (I)=ELST3 (T2 (I))
      E3 (I)=ELST3 (T3 (I))
      E4 (I)=ELST3 (T4 (I))
531  CONTINUE
      GO TO 599
C
598  WRITE (*,5001) IET
5001  FORMAT (5X,'UNKNOWN MODEL',I3,2X,'FOR MODULUS RETENTION')
      STOP
C
599  CONTINUE
C
C      RETURN
C      END
C
C      *****
C      * YIELD *
C      * COMPUTES STEEL STRENGTH
C      * FOR EACH ELEMENT
C      *****
C
C      SUBROUTINE YIELD (Fy,IFyt,TH,TC,Fyh,Fyc)
C
C      IMPLICIT REAL*8 (A-H,O-Z)
C      COMMON/SET5/ AE4(100), Io4(100), YE4(100), E4(100), FY4(100)
C      COMMON/SET7/ T1(100), T2(100), T3(100), T4(100)
C
C      TH = hot flange temperature, degrees C
C      TC = cold flange temperature, degrees C
C      Fy = steel yield strength at room temperature
C      Fyh = steel yield strength at extreme hot fibre
C      Fyc = steel yield strength at extreme cold fibre
C      T1, T2, T3, T4 are temperatures of section elements
C      Fy1, Fy2, Fy3, Fy4 are modulus retention factors for section elements
C      IFyt= indicator for the formulation of the yield strength retention
C            factor at elevated temperatures
C            1 for Gerlich (1995) formula, extended to 1000 degrees C
C            2 for Makelainen and Miller (1983) formula, extended to 1000 deg. C
C            3 for BS 5950: Part 8 formula, extended to 1000 deg. C

```

```

C
701 IF (IFyt. NE. 1) GO TO 702
    Fyh=FYT1(TH)*FY
    Fyc=FYT1(TC)*FY
    DO 711 I=1,100
    FY4(I)=FYT1(T4(I))*FY
711 CONTINUE
    GO TO 799
C
702 IF (IFyt. NE. 2) GO TO 703
    Fyh=FYT2(TH)*FY
    Fyc=FYT2(TC)*FY
    DO 721 I=1,100
    FY4(I)=FYT2(T4(I))*FY
721 CONTINUE
    GO TO 799
C
703 IF (IFyt. NE. 3) GO TO 798
    Fyh=FYT3(TH)*FY
    Fyc=FYT3(TC)*FY
    DO 731 I=1,100
    FY4(I)=FYT3(T4(I))*FY
731 CONTINUE
    GO TO 799
C
798 WRITE (*,7001) IFyt
7001 FORMAT (5X,'UNKNOWN MODEL',I3,2X,'FOR STRENGTH RETENTION')
    STOP
C
799 CONTINUE
C
C
C      RETURN
C      END
C
C
C      *****
C      * GEOM *
C      * COMPUTES MODULUS-WEIGHTED
C      * SECTION PROPERTIES
C      *****
C
C      SUBROUTINE GEOM (Ao,CG1,CG3,CG4,WI1,A2,S3c,S3t,S4c,S4t,WI3,WI4)
C
C      IMPLICIT REAL*8 (A-H,O-Z)
C      COMMON/SET2/ AE1(100), Io1(100), YE1(100), E1(100)
C      COMMON/SET3/ AE2(100), Io2(100), YE2(100), E2(100)
C      COMMON/SET4/ AE3(100), Io3(100), YE3(100), E3(100)
C      COMMON/SET5/ AE4(100), Io4(100), YE4(100), E4(100), FY4(100)
C
C      Modulus-weighted section properties (for 4 types of sections):
C      A1, A2, A3, A4      = area of section,
C      CG1, CG3, CG4      = distance from section centroid to the outside face
C                          of cold flange,
C      WI1, WI3, WI4      = section moment of inertia,
C      S3c, S3t, S4c, S4t = section modulus in bending.
C
C      Compute modulus-weighted properties for unreduced unperforated section
C
C      A1=0.0
C      CG1=0.0
C      DO 811 I=1,100
C      DUM=E1(I)*AE1(I)
C      A1=A1+DUM
C      CG1=CG1+DUM*YE1(I)
811 CONTINUE

```



```

      CG1=CG1/A1
C
      WI1=0.0
      DO 812 I=1,100
      WI1=WI1+E1(I)*(Io1(I)+AE1(I)*(YE1(I)-CG1)**2)
812 CONTINUE
C
C      Compute modulus-weighted properties for reduced section in compression
C
      A2=0.0
      DO 821 I=1,100
      A2=A2+E2(I)*AE2(I)
821 CONTINUE
C
C      Compute modulus-weighted properties for reduced section in bending
C      (hot flange compressed)
C
      A3=0.0
      CG3=0.0
      DO 831 I=1,100
      DUM=E3(I)*AE3(I)
      A3=A3+DUM
      CG3=CG3+DUM*YE3(I)
831 CONTINUE
      CG3=CG3/A3
C
      WI3=0.0
      DO 832 I=1,100
      WI3=WI3+E3(I)*(Io3(I)+AE3(I)*(YE3(I)-CG3)**2)
832 CONTINUE
      S3c=WI3/(Ao-CG3)
      S3t=WI3/CG3
C
C      Compute modulus-weighted properties for reduced section in bending
C      (cold flange compressed)
C
      A4=0.0
      CG4=0.0
      DO 841 I=1,100
      DUM=E4(I)*AE4(I)
      A4=A4+DUM
      CG4=CG4+DUM*YE4(I)
841 CONTINUE
      CG4=CG4/A4
C
      WI4=0.0
      DO 842 I=1,100
      WI4=WI4+E4(I)*(Io4(I)+AE4(I)*(YE4(I)-CG4)**2)
842 CONTINUE
      S4c=WI4/CG4
      S4t=WI4/(Ao-CG4)
C
C
      RETURN
      END
C
C
C      *****
C      * STEEL MODULUS OF ELASTICITY *
C      * RETENTION FACTOR AT ELEV.TEMP.*
C      * FORMULA 1 (Gerlich 1995) *
C      *****
C
      DOUBLE PRECISION FUNCTION ELST1(T)
C
      IMPLICIT REAL*8 (A-H,O-Z)
C
      901 IF (T. GT. 650.) GO TO 902

```

```

      ELST1=1.-3.E-4*T+3.7E-7*T**2-6.1E-9*T**3+5.4E-12*T**4
      GO TO 999
C
  902 IF (T. GT. 1000.) GO TO 903
      ELST1=0.528-0.000428*T
      GO TO 999
C
  903  ELST1=0.1
C
C
  999 RETURN
      END
C
C
C *****
C * STEEL MODULUS OF ELASTICITY *
C * RETENTION FACTOR AT ELEV.TEMP.*
C * FORMULA 2 (Makelainen and *
C * Miller 1983, steady tests) *
C *****
C
      DOUBLE PRECISION FUNCTION ELST2(T)
C
      IMPLICIT REAL*8 (A-H,O-Z)
C
  901 IF (T. GT. 800.) GO TO 902
      ELST2=-0.46*DTANH((T-550.)/250.)+0.56
      GO TO 999
C
  902 IF (T. GT. 1000.) GO TO 903
      ELST2=0.65-0.00055*T
      GO TO 999
C
  903  ELST2=0.1
C
C
  999 RETURN
      END
C
C
C *****
C * STEEL MODULUS OF ELASTICITY *
C * RETENTION FACTOR AT ELEV.TEMP.*
C * FORMULA 3 (Makelainen and *
C * Miller 1983, transient tests) *
C *****
C
      DOUBLE PRECISION FUNCTION ELST3(T)
C
      IMPLICIT REAL*8 (A-H,O-Z)
C
  901 IF (T. GT. 600.) GO TO 902
      ELST3=1.01-0.139**2.71828**(0.007*(T-346.))
      GO TO 999
C
  902 IF (T. GT. 1000.) GO TO 903
      ELST3=0.3175-0.0002175*T
      GO TO 999
C
  903  ELST3=0.1
C
C
  999 RETURN
      END
C
C
C *****
C * STEEL YIELD STRENGTH *

```

```

C      * RETENTION FACTOR AT ELEV.TEMP.*
C      * FORMULA 1 (Gerlich 1995)      *
C      *
C      DOUBLE PRECISION FUNCTION FYT1(T)
C
C      IMPLICIT REAL*8 (A-H,O-Z)
C
C      901 IF (T. GT. 650.) GO TO 902
C          FYT1=1.-5.3E-4*T+4.E-6*T**2-1.9E-8*T**3+1.7E-11*T**4
C          GO TO 999
C
C      902 IF (T. GT. 1000.) GO TO 903
C          FYT1=0.464-0.000464*T
C          GO TO 999
C
C      903 FYT1=0.
C
C      999 RETURN
C      END
C
C      *
C      * STEEL YIELD STRENGTH          *
C      * RETENTION FACTOR AT ELEV.TEMP.*
C      * FORMULA 2 (Makelainen and    *
C      * Miller 1983)                  *
C      *
C      DOUBLE PRECISION FUNCTION FYT2(T)
C
C      IMPLICIT REAL*8 (A-H,O-Z)
C
C      901 IF (T. GT. 500.) GO TO 902
C          FYT2=1.088-0.1314*2.71828**(0.0047*(T-148.3))
C          GO TO 999
C
C      902 IF (T. GT. 800.) GO TO 903
C          FYT2=104.*(1.-T/1135.)/(T-356.)
C          GO TO 999
C
C      903 IF (T. GT. 1000.) GO TO 904
C          FYT2=0.345-0.000345*T
C          GO TO 999
C
C      904 FYT2=0.
C
C      999 RETURN
C      END
C
C      *
C      * STEEL YIELD STRENGTH          *
C      * RETENTION FACTOR AT ELEV.TEMP.*
C      * FORMULA 3 (BS 5950 : Part 8)  *
C      *
C      DOUBLE PRECISION FUNCTION FYT3(T)
C
C      IMPLICIT REAL*8 (A-H,O-Z)
C
C      901 IF (T. GT. 100.) GO TO 902
C          FYT3=1.
C          GO TO 999
C
C      902 IF (T. GT. 200.) GO TO 903

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```

      FYT3=1.055-0.00055*T
      GO TO 999
C
903 IF (T. GT. 250.) GO TO 904
      FYT3=1.165-0.0011*T
      GO TO 999
C
904 IF (T. GT. 300.) GO TO 905
      FYT3=1.17-0.00112*T
      GO TO 999
C
905 IF (T. GT. 350.) GO TO 906
      FYT3=1.29-0.00152*T
      GO TO 999
C
906 IF (T. GT. 400.) GO TO 907
      FYT3=1.304-0.00156*T
      GO TO 999
C
907 IF (T. GT. 450.) GO TO 908
      FYT3=1.52-0.0021*T
      GO TO 999
C
908 IF (T. GT. 500.) GO TO 909
      FYT3=1.511-0.00208*T
      GO TO 999
C
909 IF (T. GT. 550.) GO TO 910
      FYT3=1.481-0.00202*T
      GO TO 999
C
910 IF (T. GT. 600.) GO TO 911
      FYT3=1.481-0.00202*T
      GO TO 999
C
911 IF (T. GT. 1000.) GO TO 912
      FYT3=0.6725-0.0006725*T
      GO TO 999
C
912 FYT3=0.
C
C
999 RETURN
      END

```

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Figure D.1. Flowchart of JOIST program.

Figure D.2. Thermal Elongation of Steel.

Figure D.3. Retention Factors for Steel Modulus of Elasticity at Elevated Temperatures.

Figure D.4. Reduction of Steel Yield Strength at Elevated Temperatures.

Stress-Free Thermal Bowing Deflection $D_{th} = FI \times H \times H / 8$
 Reduced Thermal Bowing Deflection $DR_{th} = RCLD \times D_{th}$
 Artificial End Moments $EM = (1 - RCLD) \times FI \times (E \times WII)$
 where
 FI = curvature of the stress-free thermal bowing
 $(E \times WII)$ = stiffness of the heated joist section for bending that causes
 compression of the hot flange.

Figure D.5. Reduction of Stress-Free Thermal Bowing and Associated End Moments.

Figure D.6. Vertical Cross-Section Details (LSF Floor FF-25).

Figure D.7. Simulated and Measured Deflections at Joist Mid-Span.

Figure D.8. Moment-Curvature Relationship for Joist Section at 45 minutes.

Figure D.9. Mid-Span Section Stress Profile at 45 minutes.

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