Influence of the design fire scenario on the response of a 10-storey steel frame: travelling fires and Eurocode

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ABSTRACT

For the design of buildings against fire the European building design code (Eurocode EN1991-1-2) considers a standard fire and parametric time-temperature curves. Standard fires are based on tests in small enclosures and thus have limitations on their applicability to large enclosures. Instead, in large open-plan compartments travelling fires have been observed and to account for such fires a design tool called Travelling Fires Methodology (TFM) has been developed in recent years by Stern-Gottfried et al. The aim of this study is to compare the structural response of a multi-storey steel frame subjected to parametric time-temperature curves and travelling fires. A two-dimensional 10-storey 5-bay steel frame is modelled in the general finite element program LS-DYNA. The program was previously verified and validated by the authors to be suitable for structural fire analysis. For each floor of the frame 6 different cases are investigated. They include four travelling fire scenarios as well as short-hot and long-cool parametric time-temperature curves. In total 60 fire scenarios are considered. The development of deflections, axial forces and bending moments is analysed. In general for both travelling fires and parametric fires the development of stresses and displacements within heated beams is found to follow similar trends irrespective of the frame floor at which a fire occurs. Parametric fires are found to result in 20 to 50 kN higher compressive axial forces in beams compared to travelling fires. However, results show small oscillations of axial forces and bending moments for the smallest travelling fire sizes, which are not observed for the parametric fires. These oscillations are found to be linked to the travelling fire size (area of the floor involved in fire) in relation to the width of the bay. Beam mid-span deflections are similar for both travelling fires and parametric fires and depend mainly on the fire duration, but the locations in the frame where these displacements occur are different. For travelling fires and parametric fires the highest deflections develop in edge bays and central bay, respectively. The results indicate that depending on the structural metric examined both travelling fires and parametric fires can result in the most severe scenario and both need to be considered to ensure a safe design.

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INTRODUCTION

Innovative architectural designs of new high rise structures pose previously unthought-of challenges to architects and engineers. This is above all the case in structural fire engineering. For the design of buildings against fire the European building design code (Eurocode EN1991-1-2) considers a standard fire and parametric time-temperature curves. Standard fires are based on tests in small enclosures and thus have limitations on their applicability to large enclosures. A survey of buildings in Edinburgh [1] has shown that only 8% of total volume of newly constructed buildings falls within these limitations. In addition, the standard fire curve and parametric time-temperature curves are based on the unrealistic assumption of uniform fire conditions in a compartment [2]. While this assumption may be suitable for small enclosures, fires in large open-plan compartments have been observed to travel resulting in a highly non-uniform temperature distributions within the enclosure [3]. Examples of such accidental events include the World Trade Centre Buildings 1, 2 & 7 (2001) and Windsor Tower fire in Madrid (2006) and One Meridian Plaza fire in Philadelphia (1991). In all of these accidents, the fires lasted for up to 7 or even 20 hours (One Meridian Plaza). Long fire durations like these are not considered in the current design codes.

Non-uniform temperature distributions on structures have been shown to have a significant impact on the failure mechanism and time to failure. In previous studies on steel [4], reinforced concrete [5] and post-tensioned concrete frames [6] where a travelling fire was considered, large distortions and a cyclic behaviour of stresses and deflection patterns have been observed. However, to represent a travelling fire the studies [4], [6] parametric curves were used and shifted from one bay to another after an arbitrary time. As noted by Stern-Gottfried and Rein [3] such representation ignores the basics of fire spread, preheating of structural elements by hot smoke and spatially varying temperatures within the compartment.

Recently, to account for travelling fires a design tool called Travelling Fires Methodology (TFM) [7], [8] has been developed. It considers a family of fires which depend on the fire spread rates and thus the percentage of the total floor area engulfed in flames. In TFM fire is divided into two regions near-field and far-field. Near-field represents the area where flames are directly impinging on the ceiling and far-field represents radially decreasing smoke temperatures further away from the fire. Therefore, TFM unlike parametric fires considers more realistic non-uniform temperature distributions in the compartment.

The aim of this study is to assess and compare the structural response of a two-dimensional generic multi-story steel frame subjected to parametric fires and travelling fires [8], which unlike previously identified studies [4], [6] accounts for spatially varying temperatures in the compartment. Another aim of this work is to investigate how varying the building floor that the fire occurs on influences the structural response of the frame.

FINITE ELEMENT MODEL

Investigated frame

The multi-story steel frame considered in this study is based on the moment resistant frame design published by NIST [9]. It is a 10-storey 5-bay frame representative of a generic office building with a floor layout of 45.5 m x 30.5 m, as shown in Figure 1. The frame is designed in accordance to the American Society of Civil Engineers (ASCE 7-02) standard. In this study
the structural fire response of a two dimensional internal frame with a beam span of 9.1 m is investigated. All columns in the frame are 4.2 m in length except for ground floor columns which are 5.3 m long.

Steel beams are designed to support a lightweight concrete floor slab. Design loads on the floor beams are 3.64 kN/m² (dead) and 4.79 kN/m² (live). For the roof design loads are 2.68 kN/m² (dead) and 0.96 kN/m² (live). The same loading on the frame is considered in this study. Beam sections are W14x22 at all floors. Column sections on floors 0 to 3, floors 4 to 6, and floors 7 to 8 are W18x119, W19x97, and W18x55, respectively. ASTM A992 structural steel with the yield strength ($F_y$) of 344.8 MPa is considered for all beams and columns. In this paper different bays are referred to as Bay 1 to Bay 5 corresponding to different beam spans from the left side to the right side of the frame. Different floors of the building are referred to as Floor 0 to Floor 9 going up from the ground floor to the top floor of the frame (see Figure 1).

It should be noted that due to the 2D representation of the building the composite action between beams and concrete floor slab are not taken into account, which has been shown to have a beneficial effect to the structural response during fire as a result of tensile membrane action [10]. 2D analysis has been chosen for reasons of computational time, in order to allow comparison of many different fire exposures and due to the fact that the Improved Travelling Firs Methodology (iTFM), which is used to represent travelling fires, defines fires spreading along a linear path. Uniform thermal profile in the perpendicular side to the travel direction is assumed.

**Fire scenarios**

In this study the structural response of the frame subjected to travelling fires (TF) and standard design fires such as Eurocode (EC) [11] parametric temperature-time curves is investigated. To represent a travelling fire exposure iTFM [8] is used. It is the most recent version of the Travelling Fires Methodology (TFM), which was developed by Stern-Gottfried, Law and Rein [3], [5], [7] to account for the travelling nature of fires. iTFM considers non-uniform temperature distribution in the compartment and long fire durations observed in...
previously identified accidents. Illustration of a travelling fire is shown in Figure 2. Each floor of the frame is subjected to four TF scenarios, 2.5%, 10%, 25%, and 48% of the floor area (which effectively represent different fire spread rates [8]), generated using iTFM. 2.5% and 48% correspond to the limits of likely realistic fire spread rates in compartments. TF sizes of 10% and 25% in previous studies [7], [12] based on different failure criteria have been found to be the worst case scenarios. In addition to that two parametric temperature-time curves are considered representing short-hot and long-cool fire exposures based on the study by Lamont et al. [13]. Therefore, in total 60 fire scenarios are considered.

Fig. 2. Illustration of a travelling fire and distribution of gas temperatures [8].

Fig. 3. Gas temperature (top) and corresponding steel beam web temperature (bottom) development at mid-span of Bay 2 for six different fire scenarios each floor of the frame was subjected to.
Travelling fires are assumed to travel from Bay 1 to Bay 5 (see Figure 1). Fuel load density and heat release rates are assumed to be 570 MJ/m² and 500 kW/m² [7], respectively. EC parametric curves were generated assuming the same fuel load density as for travelling fires and opening factors of 0.176 m⁰.₅ (short-hot) and 0.044 m⁰.₅ (long-cool) to represent different exposures. These opening factors correspond to 100% and 25% glass breakage, respectively, and result in different fire exposures as in [13].

Beams and columns are designed for 60 min and 120 min fire resistance respectively based on a limiting temperature of 550°C. This temperature is commonly accepted as the critical temperature for steel in traditional design [14]. At 550°C steel only maintains 60% of its ambient temperature strength. Steel insulation properties are taken as for high density perlite (thermal conductivity \( k_i = 0.12 \) W/m.K, density \( \rho_i = 550 \) kg/m³, and specific heat \( c_i = 1200 \) J/kg.K) [15]. Heat transfer to the structural members was carried out using lumped capacitance for separate parts of the sections (i.e. web and flanges) according to [15]. For beams the effect of the slab acting as a heat sink was taken into account. The convective heat transfer coefficient, density of steel and radiative emissivity are assumed to be 35 W/m².K, 7850 kg/m³ and 0.7, respectively [15]. The time step used for heat transfer calculations satisfying the stability criteria is 10 s. Gas temperatures and corresponding beam temperatures for all fire scenarios at the mid-span of Bay 2 are shown in Figure 3. Gas temperatures for Floor 0 are lower in comparison to the other floors because of the higher floor height (floor 0 – 5.3 m, floors 1 to 9 – 4.2 m).

**LS-DYNA model**

The multi-storey steel frame is modelled using general purpose multi-physics finite element program LS-DYNA [16]. It was originally developed for highly nonlinear and transient dynamic analysis. LS-DYNA is capable to simulate thermal and thermal-structural coupling analysis and has an extensive element and material library including the temperature dependent material models from the Eurocode. Prior to this analysis the program was validated and verified by the authors against the available benchmarking and fire test data for structural fire analysis [17]. All of the parameters for the model presented in this section were chosen based on the mesh density and parameter sensitivity studies. Steel beams and columns are modelled using Hughes-Liu beam formulation with an integration refinement factor of 5. Beams, Floor 0 columns, and Floor 1 to 9 columns are divided into 36, 22, and 16 beam elements, respectively. Corresponding beam element length is approximately 0.25 m. Supports for the ground floor columns are assumed to be fixed, and the beams and columns are assumed to be rigidly connected.

Material type 202 formulation is used for both steel beams and columns with default Eurocode [18] temperature dependent material properties. Steel with initial yield stress of 345 MPa, Young’s modulus of 210 GPa [19], Poisson’s ratio of 0.3 [19], and density of 7850 kg/m³ [18] is assumed for all members. Both mechanical and gravity loading are considered. Non-uniform temperature distribution through the beam section is applied using a thermal variable load card. Temperatures are assigned to the members on the heated floor only. The remainder of the frame is assumed to be at room temperature. Simulations are carried out using the explicit solver of LS-DYNA. Therefore, in order to reduce the computational time, the temperature development within heated members is scaled by a factor of 100. This means that parametric curve which would last 120 min in ‘real’ life in the simulation would be applied in 1.2 min.
RESULTS AND DISCUSSION

Location of the fire floor

Development of the beam displacements and axial forces at the mid-span with time for the frame subjected to 48% travelling fire is shown in Figure 4. Shaded areas represent the range of the displacements and axial forces which develop within the specific beam in relation to the fire location (i.e. fire floor) for different fire floors. Numbers 0 and 9 indicate that fire is located on ground floor and top floor, respectively. Development of mid-span displacements and axial forces within these floors is different compared to fire occurring on the intermediate floors due to the reduced number of floors above or below the fire floor and different column sizes, i.e. different level of restraint. For example, beams on Floor 9 are only connected to the columns on the same floor leading to a low level of restraint to thermal expansion, while beams in intermediate floors are connected to and restrained by the columns from the floor above as well. This results in higher restraint and consequently higher axial forces by up 230 kN to as can be seen in Figure 4. Beams on ground floor have the highest restraint to thermal expansion as they are connected to columns with fixed supports.

The results indicate that in general the development of stresses and displacements follows a similar behaviour pattern for all members even though the fire occurs on different floors. The lowest limiting axial force values correspond to fire occurring on Floor 8. As the fire floor number reduces, the axial force in the heated beams increases (by approx. 60 kN, 16%). On the other hand, higher displacements (by approx. 30 mm, 7.7%) develop within beams when fire occurs on the top floors of the building rather than the bottom. This is because heated beams on the top floors of the frame are supported by weaker column sections than beams on the bottom floors. Thus, the restraint to thermal expansion and redistribution of stresses is smaller in the upper floors. Results indicate that in the cases when the fire occurs in the upper floors initiation of yielding within the heated beams occurs up to 6 min later than in the cases when fire occurs on the lower floors. Yielding takes place when compressive axial force begins to decrease followed by elasto-plastic response and sudden increase in deflection [20]. Analogous results for displacement, axial force, and bending moment in different fire floor were observed for all scenarios (i.e. 2.5%, 10%, and 25% travelling fires and EC curves).

![Fig. 4. Variation of displacement and axial force development within beams with different floors of the building exposed to a 48% travelling fire (shaded areas). Numbers indicate axial force and displacement development when fire occurs on ground floor (0) and top floor (9).](image)
Figure 5 shows the development of axial forces within different beams in the frame for a 25% travelling fire on floor 2. In each bay the development of axial forces in the heated floor and in the floors above and below the fire follows the same trend. Compressive axial force develops within the heated beams while tensile axial forces develop in beams in the adjacent floors. The highest axial forces are transferred to the beams in the floors immediately above and below the fire floor. The axial force within these beams is approximately 60 to 70% of the axial force in the heated beams. This drops to 5 to 15% on the floors further away from the fire by one floor. No significant axial forces were observed in other floors. This indicates that the stress distribution is negligible in the frame floors more than 2 floors away from the fire. Similar results were observed for all other fire scenarios occurring in the intermediate floors.

**Effect of fire scenario – travelling fires and parametric curves**

The typical deflected shape of the frame and comparison of axial force, bending moment and mid-span displacement development within heated beams for different fire exposures are shown in Figure 6 and Figure 7, respectively. For all travelling fire (TF) scenarios beam displacements in Bay 1 are relatively low in comparison to other bays. Once the cooling begins the displacements remain constant while in the other bays there is a small recovery. This is because beams in Bay 1 reach lower temperatures than beams in other bays, thus resulting in lower thermal expansion and lower compressive axial forces in Bay 1. Axial forces increase bending moments and in turn deflections due to P-Δ effect [21]. For the same reason, the peak displacement reached in Bay 1 keeps on increasing with decreasing fire size as the beam is exposed to near-field for a longer duration. Higher displacements initially develop in Bay 3 for the EC fires and in Bays 1 or 2 for the travelling fires. For the short-hot EC fire and 48% TF, displacements develop more rapidly at the early stages of the fire. However, the peak values reached during the latter scenarios are at least 20 cm lower than for other fire cases.

In general, maximum deflections reached are higher for fire scenarios with longer fire durations including 2.5%, 10% and 25% travelling fires and EC long-cool fire than for shorter and hotter fires (45% TF and EC short-hot fires). This agrees with the findings by Lamont et al. [13] on short-hot and long-cool parametric fires. Short and hot fires were observed to result in faster initial displacements while long and cool fires resulted in larger maximum displacements but later during the fire. Thus, travelling fires depending on their duration
could be grouped into similar categories as well. The main difference between travelling fires and parametric fires in general appears to be that they result in different locations where the maximum deflections develop. For travelling fires and parametric fires the highest deflections develop in edge bays and central bay, respectively.

For all fire scenarios compressive axial forces in edge bays are significantly lower than in internal bays. This is because the restraint to thermal expansion is provided by only one column on one of the sides. The highest axial forces develop when the frame is subjected to large fire sizes (e.g. EC fires and 48% TF) with more uniform temperature distributions. Axial forces under these fires are 20 kN and 50 kN higher in comparison to 25% and 10%, and 2.5% travelling fires respectively. Under EC fires and 48% TF all beams in the floor are either in compression or tension at the same time, while under smaller travelling fire exposures this is not the case. This is because the total thermal expansion even if beams reach much lower peak temperatures exposed to uniform parametric fires is larger than in beams with very high but localised peak temperatures. For example beams exposed to the EC short-hot fire and 2.5% TF reach the peak temperatures of 367°C and 578°C, respectively, but the peak compressive axial force for EC short-hot fire is 55 kN higher than for 2.5% TF.

Peak mid-span bending moments for all fire scenarios are in the same range up to 160 kNm. Larger bending moments tend to develop first in Bay 2 for travelling fire scenarios, and Bay 3 for EC parametric fires. Figure 7 also shows small oscillations of bending moments and axial forces for 2.5% and 10% travelling fires. This appears to happen because fire length for these cases is shorter than the bay length. Therefore any column in the frame is exposed to high near-field temperatures when the fire crosses from one bay to another bay. This results in the change of restraint level to the heated beams and redistribution of bending moments. In other fire scenarios at least one column is always in the near-field region. Cyclic axial forces as identified in the introduction can also be observed in the work by Bailey et al. [4]. Such cyclic loading could have an influence on further material degradation. No cyclic forces are present for parametric fire or large fire size TF exposures.

### 25% travelling fire:

![Deflected shape](image1.png)

### EC long-cool parametric fire:

![Deflected shape](image2.png)

Fig. 6. Deflected shape of the frame subjected to 25% travelling fire (top) and long-cool EC fire (bottom) on Floor 7 at different times of fire exposure. Displacement scale factor is 5.
CONCLUSIONS

In this study, structural response of a generic steel frame exposed to travelling fires and the parametric fire curves on different floors of the building has been investigated. Results indicate that when different floors of the frame are subject to the same fire exposure for both travelling and parametric fires, the development of displacements and stresses within heated beams is similar, except for fires on ground floor and top floor. Higher displacements and lower axial forces develop within beams in the upper floors where column section reduces in size.

Rate and magnitude of the highest beam mid-span deflections depend mainly on the fire duration and not fire type (TF and EC parametric fire). Short and hot fires result in faster development of deflections while long and cool fires result in larger peak deflections. The same observations were made by Lamont et al. [13]. On the other hand, the locations where these peak deflections occur are different for TF and parametric fire scenarios. For travelling
fires and parametric fires the highest deflections develop in edge bays and central bay, respectively. In general, parametric fire scenarios are found to result in 20 to 50 kN larger compressive axial forces in comparison to travelling fires while peak bending moments are in the similar range for both travelling fires and parametric fire curves. When the frame is subjected to travelling fire scenarios smaller than the width of the bay small oscillations of axial forces and bending moments are observed. This is not the case when the frame is exposed to parametric fires or large size travelling fires.

These results indicate that in order to ensure a safe building design a range of different fires including both travelling fires and Eurocode fires need to be considered. While uniform fires might lead to higher axial forces travelling fires might result in larger displacements and either of them can lead to failure.

REFERENCES

14. Kirby, B. R., “Recent developments and applications in structural fire engineering