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Collapse Initiation and Mechanisms for a Generic Multi-storey Steel Frame Subjected to Uniform and Travelling Fires

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Abstract

To ensure that fire induced collapse of a building is prevented it is important to understand the sequence of events that can lead to this event. In this paper, the initiation of collapse mechanisms of generic a multi-storey steel frame subjected to vertical and horizontal travelling fires are analysed computationally by tracking the formation of plastic hinges in the frame and generation of fire induced loads. Both uniform and travelling fires are considered. In total 58 different cases are analysed using finite element software LS-DYNA. For the frame examined with a simple and generic structural arrangement and higher applied fire protection to the columns, the results indicate that collapse mechanisms for singe floor and multiple floor fires can be each split into two main groups. For single floor fires (taking place in the upper floors of the frame (*Group S*1)), collapse is initiated by the pull-in of external columns when heated beams in end bays go into catenary action. For single floor fires occurring on the lower floors(*Group S*2), failure is initiated (i.e. ultimate strain of the material is exceeded) after the local beam collapse. Failure in both groups for single floor fires is governed by the generation of high loads due to restrained thermal expansion and the loss of material strength. For multiple floor fires with a low number of fire floors (1 to 3) - *Group M*1, failure is dominated by the loss of material strength and collapse is mainly initiated by the pull-in of external columns. For the cases with a larger number of fire floors (5 to 10) - *Group M*2, failure is dominated by thermal expansion and collapse is mainly initiated by swaying of the frame to the side of fire origin. The results show that for the investigated frame initiation of collapse mechanisms are affected by the fire type, the number of fire floors, and the location of the fire floor. The findings of this study could be of use to designers of buildings when developing fire protection strategies for steel framed buildings where the potential for a multifloor fire exists.

Keywords: Fire safety, tall buildings, collapse mechanisms, multi-storey fires, travelling fires

1. Introduction

In recent years, there have been several large fire accidents which led to either partial or complete collapse of a structure. They include, for example, the WTC Tower 1, 2, &7 fires in New York (2001), the Windsor Tower fire in Madrid (2005), the Faculty of Architecture building fire at TU Delft in the Netherlands (2008), and the Plasco building fire in Tehran (2017). To ensure that fire induced collapse of a building is prevented it is important to understand the sequence of events that can lead to this event.

Many studies have been conducted since the mid-nineties with the objective of better understanding the mechanisms of collapse of structures subjected to fire (Agarwal and Varma 2014; Alderighi and Salvatore 2009; Ali et al. 2004; Bailey et al. 1999; Becker 2002; El-Rimawi et al. 1999; Flint et al. 2007; Kilic and Selamet 2013; Kotsovinos and Usmani 2013; Lange et al. 2012; Liew et al. 1998; Porcari et al. 2015; Shepherd and Burgess 2011; Wang 2000) and the effectiveness of various bracing systems in preventing the collapse (Sun et al. 2012; Jiang et al. 2014). Generally, when unrestrained structural elements are heated, thermal expansion results in a geometric change to the structural element. Without restraint this geometric change is accommodated without the development of any mechanical loads. However, in real structures exposed to fire this geometric change is typically partially restrained by the adjacent cooler structure which results in the development of significant restraining forces in conjunction with some displacement. Differential relative expansion of connected elements can result in the generation of large axial forces and bending moments within the structure. Continued heating and increasing displacement can lead to the mobilisation of alternative load carrying mechanisms which are otherwise not normally relied upon under ambient conditions, such as catenary or membrane mechanisms. These alternative mechanisms result in further loads being applied to the supporting structure. In BRE tests (Bailey et al. 1999; Wang 2000) and computational analysis of 2D steel

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frames (Bailey et al. 1999; El-Rimawi et al. 1999), the results showed generation of large bending moments in the columns, which were pushed by expanding connected beams. These additional forces generated in a structure due to a fire can result in a local failure of a structural member initiating partial or complete global collapse.

Research on various steel framed structures (Agarwal and Varma 2014; Bailey et al. 1999; Liew et al. 1998) in which columns were left unprotected or had the same level of protection as beams have indicated columns to be the critical members. In these studies collapse was initiated by the buckling of columns. In the cases where columns were assumed to be protected and have a higher level of protection than beams, failure was governed by large beam deflections (Liew et al. 1998) and pull-in of external columns (Flint et al. 2007; Porcari et al. 2015). After local beam or column failure, the loads are redistributed to adjacent cooler and stiffer structure. Generally, in research studies (Alderighi and Salvatore 2009; Flint et al. 2007) global collapse was found to occur due to the inability of structure to transfer the load after local failure.

Flint et al. (2007), Lange et al. (2012), Kotsovinos and Usmani (2013) have identified and studied two main types of collapse mechanisms, i.e. weak-floor and strong-floor, of tall structures with both long-span composite truss system and with more traditional composite floor systems. The collapse mechanisms identified are caused by the horizontal pull-in forces applied to an external column by a fire affected floor adopting a catenary mechanism. These pull-in forces can lead to either the buckling of the floor below the fire floors (weak-floor mechanism) or due to the formation of three hinges in an external column (strong floor mechanisms). Ali et al (2004) identified two collapse modes of single-storey steel frames depending on the location of fire. In the first mode, the frame collapsed inward due to the catenary action in beams, while in the second mode, when the fire was located close to the edge column, the frame collapsed outward due to the loss of strength of columns. In the second mode, the extent of the heated portion of the beam was not sufficient to cause catenary force (Ali et al. 2004). In 2015, Porcari et al (2015) carried out an extensive literature review on the progressive collapse of steel structures subjected to fire and devised two extreme possible structural response scenarios of unprotected steel structures. The two scenarios were related to the slenderness of the structural members, load ratio, presence of the lateral bracing, and weak-floor and strong-floor collapse mechanisms identified in (Flint et al. 2007; Kotsovinos and Usmani 2013; Lange et al. 2012).

Collapse mechanisms of buildings subjected to travelling fires have only been studied by Kotsovinos and Usmani (2013) for tall structures with long span composite truss system. In this paper, initiation of collapse of a different structure, i.e. generic multi-storey steel frame, subjected to vertical and horizontal travelling fires are analysed. Both uniform and travelling fires are considered. The location of the single fire floor in the frame and the number of simultaneously heated fire floors are varied.

2. The Structural Frame

The multi-storey steel frame considered in this analysis is based on the moment resisting frame published by NIST (Sadek et al. 2011). It is a 10-storey 5-bay frame, representative of a generic office building, with a floor layout of 45.5 m × 30.5 m. It is designed according to the American Society of Civil Engineers (ASCE 7-02) standard. The plan layout and elevation of the building are shown in Figure 1. In this study the structural fire response of a 2D internal frame with the longest beam span of 9.1 m is investigated, continuing previous work by the authors (Rackauskaite et al. 2017a, 2017b, 2019). All columns in the frame are 4.2 m in height except for the ground floor columns which are 5.3 m high. The frame is modelled

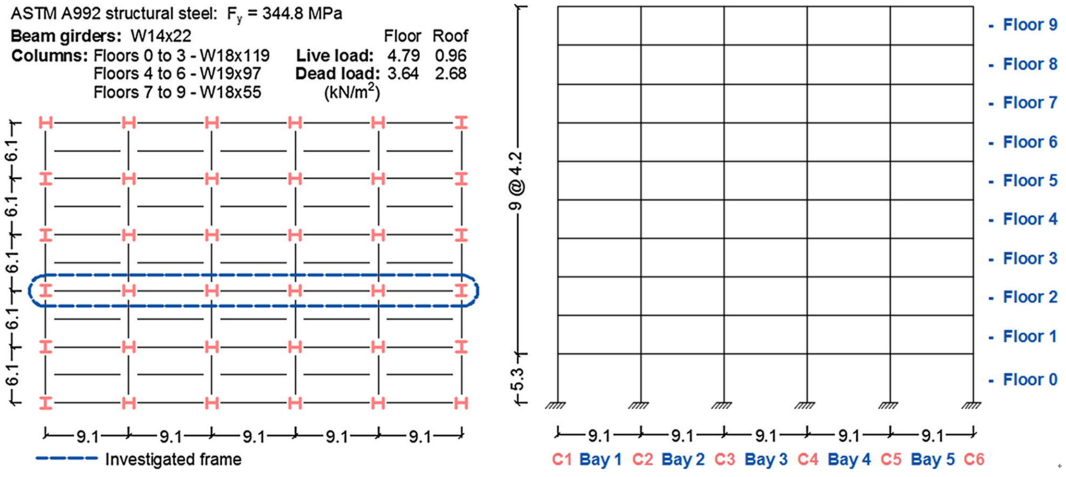


Figure 1. The structural frame considered in this paper. Frame dimensions are given in meters.

using the finite element software LS-DYNA Release 7.1.1 (for more details on the model the reader is referred to (Rackauskaite et al. 2017a, 2017b, 2019)).

It should be noted that due to the 2D representation of the building, the composite action between the beams and the concrete floor slab is not taken into account in the model. This is unlikely to impact on the initiation of collapse and on the mechanisms, which lead to that. However, the flexure and axial compression in the floors is likely to be affected and requires a further study which is outside the scope of this publication. The 2D representation is considered to be acceptable for this study as the primary objectives are to analyse the general trends and to compare the outcomes of the model for the different fire scenarios considered.

3. Cases Considered

The cases considered include single floor and multiple floor uniform (ISO, SFPE, and EC LC) and travelling fire scenarios (2.5%, 10%, 25%, and 48% TFM) for which failure occurred during the fire exposure as reported in (Rackauskaite et al. 2017a, 2017b, 2019). ISO, SFPE, EC LC, and TFM correspond to a standard fire, constant uniform temperature of 1200°C from the SFPE standard, Eurocode long-cool fire, and travelling fire as in (Rackauskaite et al. 2017a, 2017b, 2019).

In total 58 different cases are studied, an overview of which is given in Table 1. Initiation of failure and collapse is analysed by tracking the formation of plastic hinges in the frame, and generation of axial forces and bending moments in different structural members (analysed in (Rackauskaite et al. 2017a, 2017b, 2019)). In this paper, failure refers to the local element failure when ultimate strain of the material is exceeded, while 'collapse' refers to the initiation of the global failure of the frame. For both single floor and simultaneous multiple floor fires, different cases are grouped and presented based on the similarities in the initiation of collapse mechanism. This study only analyses the initiation of collapse in the terms of global structural response. That is, local phenomena such as connection failure or local buckling of flanges or web of structural members are not included in the model and, therefore, not considered in the analyses, although they may govern during the progression of collapse.

It should be noted that it is recognised that a number of fully developed fire scenarios involving multiple floors simultaneously are assessed in this work which is not common design practice due to the intent of the requirements in fire safety regulation, other fire safety measures generally provided in buildings, the time required for vertical fire spread and fire to develop within a particular floor plate. It is not implied that all buildings need to be assessed under any or all these scenarios (noting that for tall buildings a multiple floor fire has been considered for additional robustness by some designers). However, for the purposes of this work, despite some of these scenarios being potentially academic in nature, they have been considered in order to establish the trends in fire induced collapse mechanisms.

4. Results

4.1. Single floor fires

4.1.1. Uniform fires, Floors #6-#9

The illustration of the defected shape, generation of plastic hinges and change in bending moments with time for a steel frame exposed to ISO fire on Floor #6 are shown in Figure 2 and 3. As identified in (Rackauskaite et al. 2019), frame even at ambient temperature is under a high level of utilization, particularly the beams. At ambient temperature, beams in Bays 1 & 5 and upper floors of the frame experience the highest bending moments (by 5 kNm higher in Floor #7 than in Floor #6). Therefore, as the heated beams begin to expand and generate additional axial forces due to restrained thermal expansion in the heated floors and floors above and below the fire, yielding first takes place in the unheated beams on Floor #7 at 11 min. Then, beam in Bay 3 yields due to the development of large axial forces and bending moments because of high axial restraint from the surrounding structure. It is followed by yielding of beams in Bays 2 & 4, and Bays 1 & 5.

Loads generated during the fire are redistributed to the adjacent cool structure. This results into the generation of high bending moments and thus yielding of the unheated

Table 1. Summary of the cases considered in this paper

Fire type	Single floor fires (Rackauskaite et al. 2017a, 2019): Fire floors (#)	Multiple floor fires (Rackauskaite et al. 2017b): Number of fire floors
ISO	#0, #1, #2, #3, #4, #5, #6, #7, #8, #9	2, 3, 5, 7, 9, 10
SFPE	#0, #1, #2, #3, #4, #5, #6, #7, #8, #9	-
EC LC	#6, #7	-
2.5% TFM	#5, #6, #7, #8	2, 3, 5, 7, 9
10% TFM	#6, #7, #8	2, 3, 5, 7, 9, 10
25% TFM	#7, #8	2, 3, 5, 7, 9, 10
48% TFM	-	5, 7, 9, 10

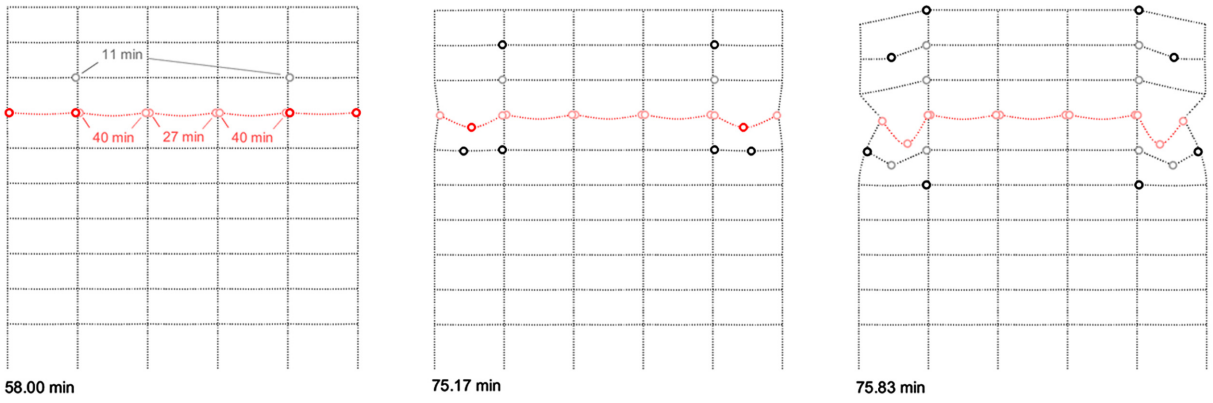


Figure 2. Deflected shape of the frame and formation of yielding points and plastic hinges (circles) at different times of fire exposure for a steel frame subjected to ISO fire on Floor #6. Red colour indicates the floor subjected to fire.

end beams in Floor #5. A significant reduction in the bending moments in Floor #6 and increase in Floor #5 after all the beams on the heated Floor #6 have yielded can be observed in Figure 3. Following this, initiation of collapse begins, when the subjected to fire beams in Bay 5 experience catenary action and pull-in the external columns. As the catenary action begins (i.e. tensile forces are generated), the loads are transferred to the beams directly below and above the fire floor, which then yield. The results indicate the beginning of the plastic collapse mechanism when all the beams in Bay 5 above the fire floor have yielded, i.e. the structure is no longer able to redistribute the load. This is followed by the ultimate strain failure in subjected to fire Floor #6 Bay 5. Similar

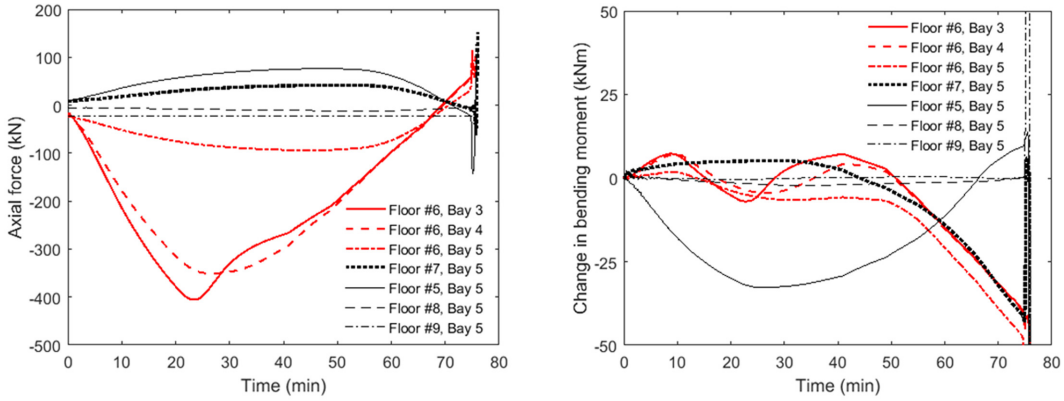


Figure 3. Generation of bending moments near connections and axial forces with time for selected beams in the frame subjected to ISO fire on Floor #6. Red colour indicates the floor subjected to fire.

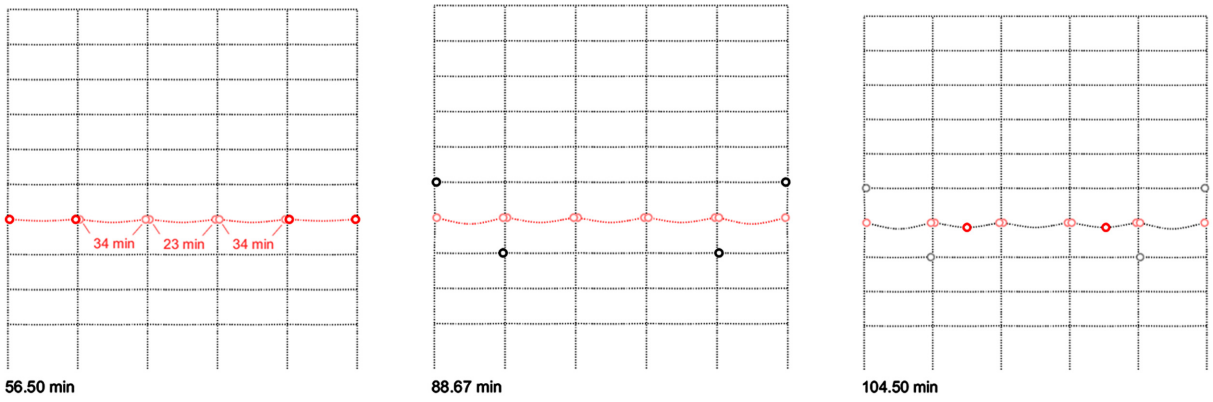


Figure 4. Deflected shape of the frame and formation of yielding points and plastic hinges (circles) at different times of fire exposure for a steel frame subjected to ISO fire on Floor #3. Red colour indicates the floor subjected to fire.

collapse and failure mechanism was observed for the cases where the frame has been subjected to ISO and SFPE fire on Floors #6 - #9 and Eurocode LC fire on Floors #6 and #7.

4.1.2. Uniform fires, Floors #0-#5

The illustration of the deflected shape, generation of plastic hinges and change in bending moments and axial forces with time for a steel frame exposed to ISO fire on Floor #3 are shown in Figure 4 and 5. Similar to ISO fire occurring on Floor #6, the subjected to fire beams in Bay 3 yield first, followed by Bays 2 & 4, and Bays 1 & 5 due to restrained thermal expansion generated forces. However, cool beams in the floor above the fire only yield after all the beams on the fire floor have yielded, unlike for the cases discussed in the previous section. This is because bending moments in beams on Floor #4 are lower than on Floor #8 at ambient temperature and additional forces generated at the beginning of fire exposure are not sufficient to cause yielding before the heated beams yield.

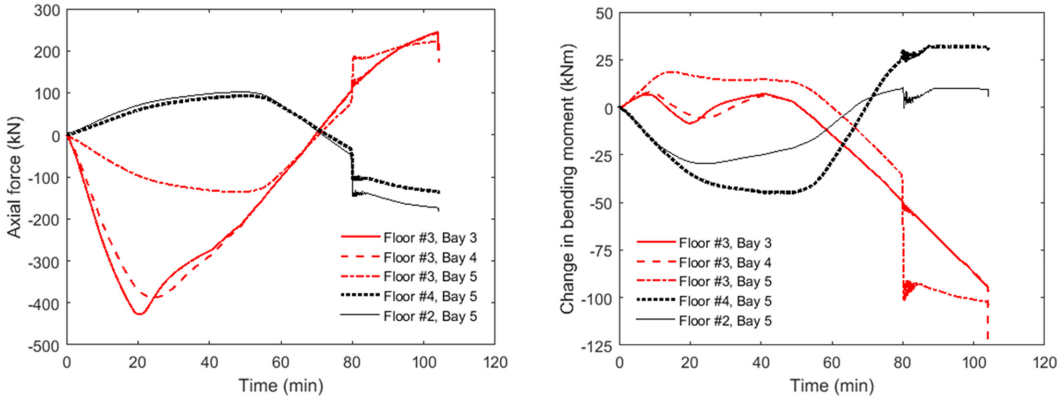


Figure 5. Generation of bending moments near connections and axial forces with time for selected beams in the frame subjected to ISO fire on Floor #3. Red colour indicates the floor subjected to fire.

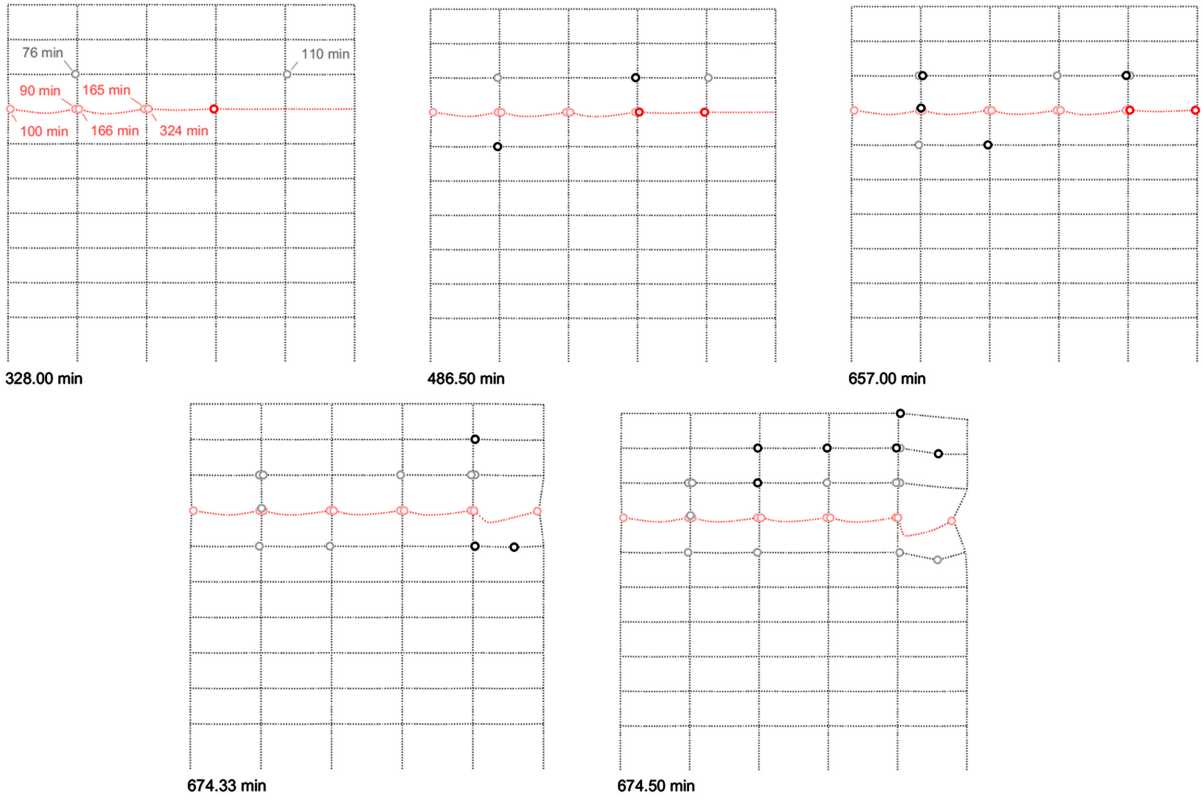


Figure 6. Deflected shape of the frame and formation of yielding points and plastic hinges (circles) at different times of fire exposure for a steel frame subjected to 2.5% TFM fire on Floor #6. Red colour indicates the floor subjected to fire.

In this case, the fire floor is adjacent to stiffer columns than on the upper floors. These columns are stronger and, therefore, able to resist pull-in and redistribute the load when beams go into catenary action. As a result, collapse is initiated later than for a fire on Floor #6 and it is caused by the formation of beam collapse mechanism in the internal subjected to fire Bays #2 and #4. Similar collapse mechanism was observed for the cases where the frame has been subjected to ISO and SFPE fires on Floors #0 - #5.

4.1.3. Travelling fires, Floors #5-#9

The illustration of the deflected shape and generation of plastic hinges with time for a steel frame exposed to the 2.5% TFM fire on Floor #6 is shown in Figure 6. As for the ISO fire, yielding first takes place in the cool beam in Bay 1 above the fire floor. It is followed by yielding of beams in the fire floors, as fire travels along the frame generating high loads due to restrained thermal expansion. Due to the redistribution of high loads, members above and below the fire floor yield as well. Collapse is initiated when the fire reaches the far end of the frame (i.e. Bay 5) and the beam goes into catenary action pulling in the end column C6. Figure 7 shows change in bending moments within structural members adjacent to Bay 5. Results indicate that as the heated beam in Bay 5 goes into tension, additional bending moments are generated in the connecting columns, C6. These moments are redistributed to the upper floors causing yielding of unheated members, and reduced robustness of the structure. Once all the beams in Bay 5 above the fire floor yield, plastic collapse mechanism is formed and ultimate strain failure in the heated beam in Bay 5 is reported.

A similar collapse mechanism by pull-in of column C6 and formation of plastic hinges in Bay 5 above the fire floor develops for a frame subjected to 2.5% TFM on Floors #5, #7, and #8; 10% TFM on Floors #6 - #8 (see Figure 8); and 25% TFM on Floors #7 & #8 (see Figure 9). However, for the 10% TFM and the 25% TFM on Floors #7 and #8 beams in the floor below the fire floor do not yield until beams in Bay 5 go into catenary action. This is because, heated beams on these floors are restrained by more slender columns (i.e. less stiff) than on the lower floors of the structure and the additional forces that develop during the fire due to restrained thermal expansion

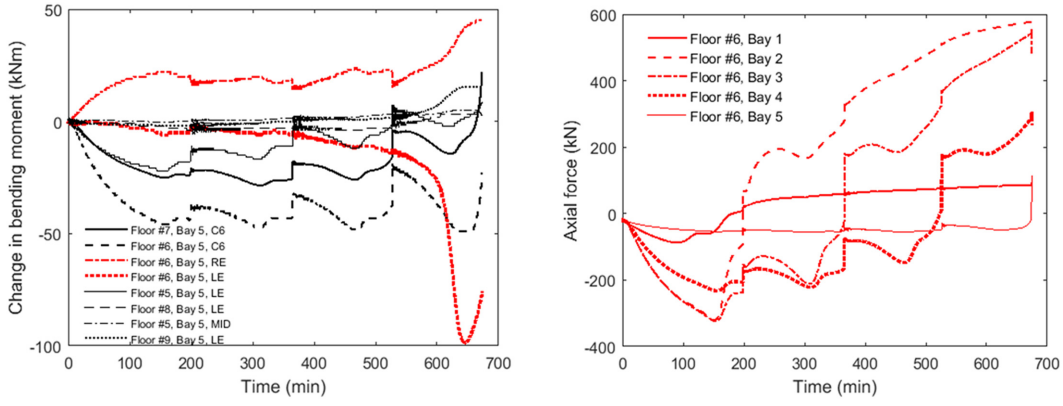


Figure 7. Generation of bending moments and axial forces with time for selected structural members of the frame subjected to 2.5% TFM fire on Floor #6. Red colour indicates the floor subjected to fire. C6, RE, LE, and MID refer to Column 6, and right end, left end, and middle of the beam, respectively.

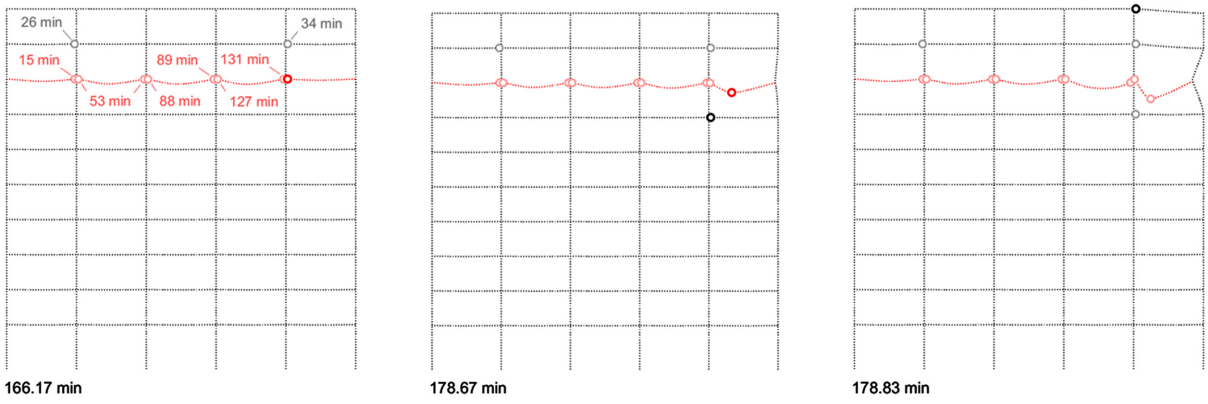


Figure 8. Deflected shape of the frame and formation of yielding points and plastic hinges (circles) at different times of fire exposure for a steel frame subjected to 10% TFM fire on Floor #7. Red colour indicates the floor subjected to fire.

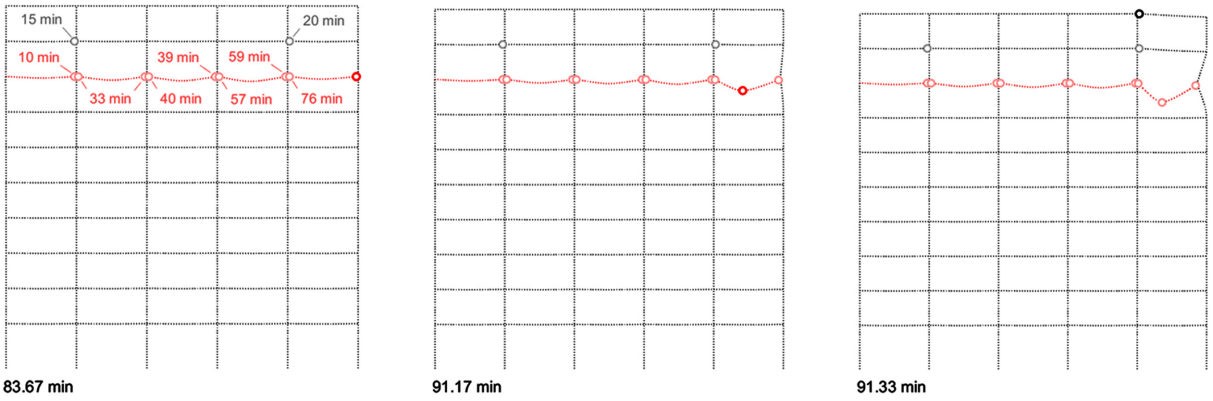


Figure 9. Deflected shape of the frame and formation of yielding points and plastic hinges (circles) at different times of fire exposure for a steel frame subjected to 25% TFM fire on Floor #7. Red colour indicates the floor subjected to fire.

are relatively smaller. For example, axial forces are lower by up to approx. 70-100 kN (10-35%) than in the floors below. For the same reason, beam end in Bay 1 connected to column C1, does not experience yielding.

4.2. Multiple floor fires

4.2.1. Standard fire – ISO

Figure 10 and Figure 11 illustrate the deflected shape and the generation of plastic hinges with time for a steel frame exposed to ISO fire on 2-floors and 5-floors, respectively. In this case, beams in the cool floors directly above and below the fire floors yield first. This is because axial forces and bending moments generated in these floors due to load redistribution in the fire floors are higher than in the fire floors (see Figure 12). At 30 min axial forces in Floor #3 Bay 1 are higher by 26 kN (40%) than in Bay 1 of the heated Floors #4 and #5. Then, as for the single floor fires, heated beams in the internal bays yield first followed by the end bays. Additional forces that develop in internal bays due to restrained thermal expansion are higher because of the higher axial restraint from the surrounding structure and, therefore, they yield

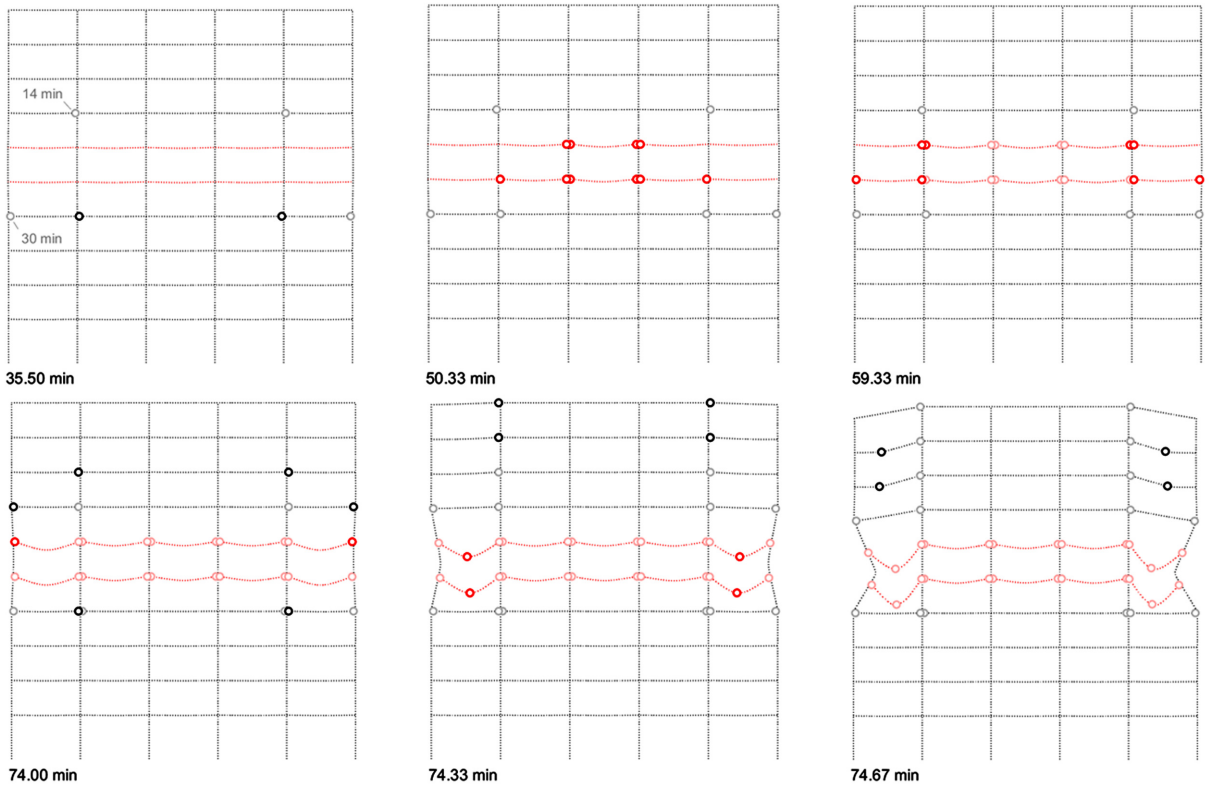


Figure 10. Deflected shape of the frame and formation of yielding points and plastic hinges (circles) at different times of fire exposure for a steel frame subjected to ISO fire on 2-floors simultaneously. Red colour indicates the floor subjected to fire.

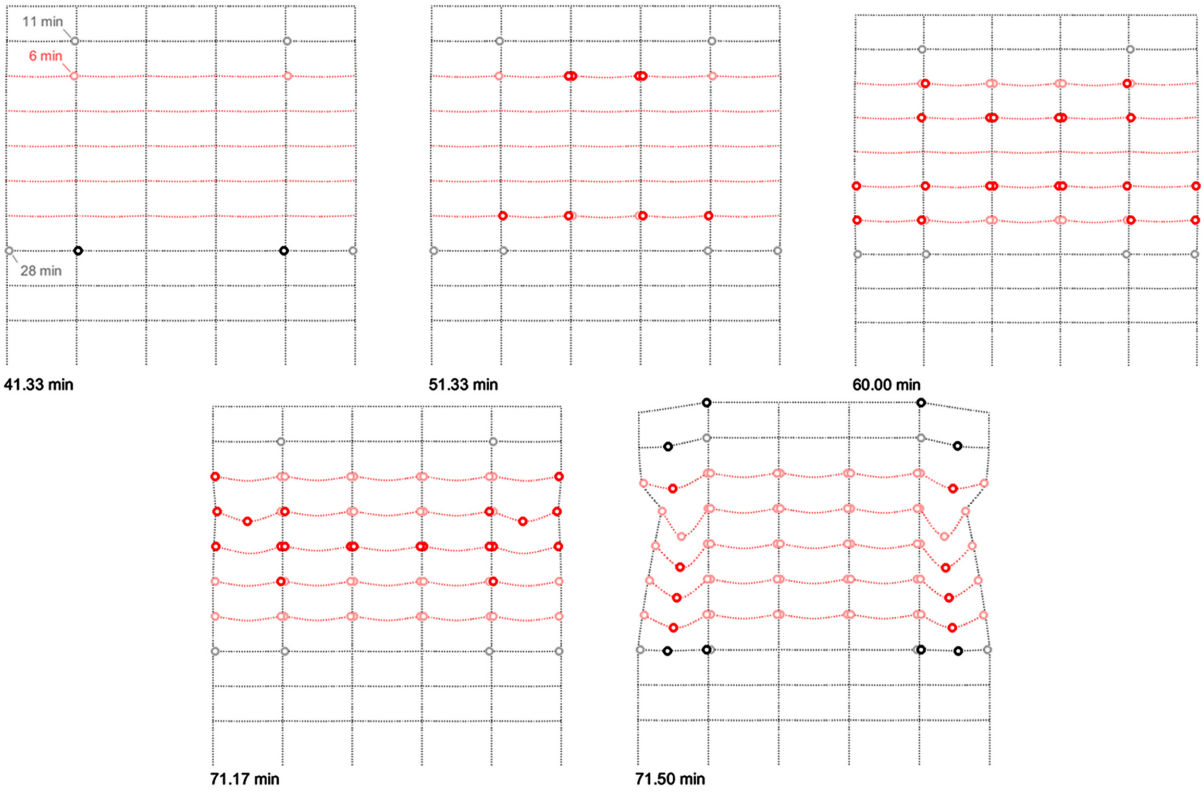


Figure 11. Deflected shape of the frame and formation of yielding points and plastic hinges (circles) at different times of fire exposure for a steel frame subjected to ISO fire on 5-floors simultaneously. Red colour indicates the floor subjected to fire.

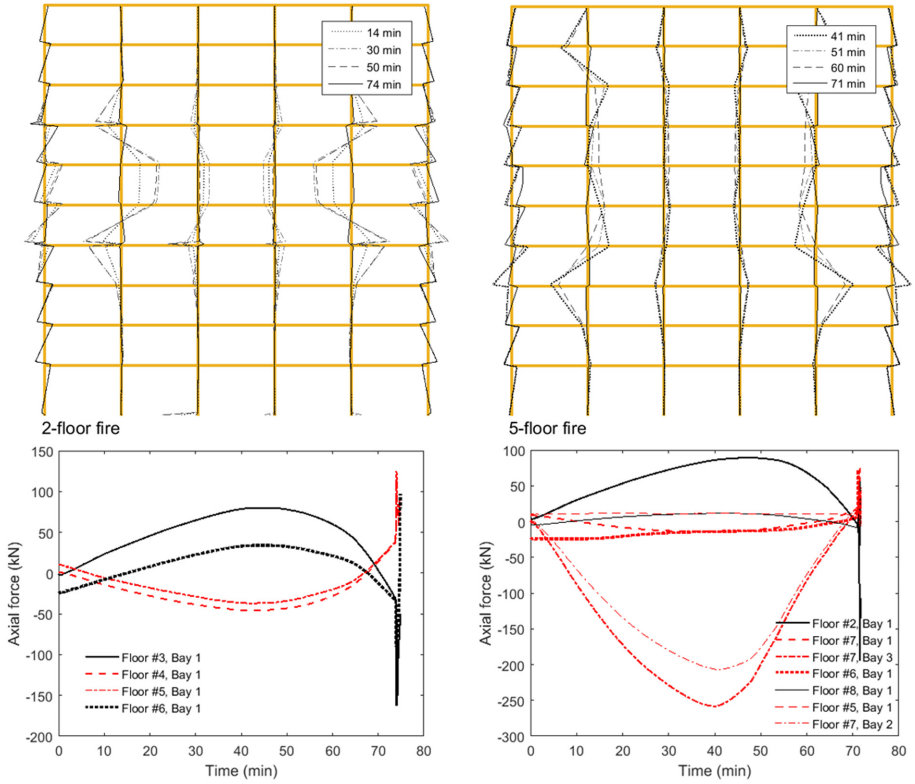


Figure 12. Generation of column bending moments (top) and beam axial forces (bottom) with time for selected beams in the frame subjected to ISO fire on 2-floors (left) and 5-floors(right). Red colour indicates the floor subjected to fire.

earlier. Figure 12 also shows that axial forces in the lower heated floor, Floor #4, are higher than in the upper heated floor, Floor #5, causing earlier yield times in the lower floor. Collapse is initiated when subjected to fire beams in Bays 1 and 5 go into catenary action and begin to pull-in the columns C1 and C6. Due to the transfer of the load to adjacent structure beams in the upper bays yield as well and the plastic collapse mechanism is initiated. Unlike for ISO fire occurring on a single Floor #4 or #5, frame for a 2-floor fire occurring on the same floors is unable to resist the cumulative load from both fire floors and transfer to the surrounding structure.

For a frame exposed to ISO fire on 5-floors (Figure 11), as for the 2-floor fire, yielding begins in the end bays (Bays 1 and 5) of cool floors directly above and below the fire floors due to high bending moments and axial forces that are generated within these floors. It is then followed by yielding of the beams on the highest (Floor #7) and lowest (Floor #3) heated floors begging at the internal bay. This is because these floors are subjected to the highest axial forces (see (Rackauskaite et al. 2017b) and Figure 12). The load is then redistributed and yielding takes place in intermediate fire floors (Floors #4 and #6) followed by the central fire floor (Floor #5). Collapse is initiated when heated beams go into catenary action. Due to load redistribution, cool beams in end bays of Floor #9 yield allowing for pull-in of external columns, because the frame cannot transfer the load anymore. A plastic collapse mechanism forms. Columns are pulled-in on heated Floors #6 and #7 where column section reduces in size. They have the lowest stiffness to resist the tensile forces in adjacent heated beams and, therefore, are pulled-in first. Similar collapse mechanism was observed for all the cases where the frame has been subjected to ISO fire on multiple floors.

4.2.2. 2.5% TFM

The illustration of the deflected shape and the generation of plastic hinges with time for a steel frame exposed to 2.5% TFM fire on 2-floors, 3-floors, and 5-floors simultaneously is shown in Figure 13, Figure 14, and Figure 15, respectively. In all of the cases heated beams in Bay 1 yield first, followed by Bay 2, etc., as the fire travels along the frame. Beams in the highest and lowest subjected to fire floors yield first as they experience higher forces due to restrained thermal expansion (see (Rackauskaite et al. 2017b) and Figure 16). Then, due to load redistribution, beams in the upper and lower unheated floors yield as well. Redistribution of the bending moments in the frame at different times of fire exposure for 2-floor and 5-floor fires in illustrated in Figure 16. For a 2-floor fire, yielding of the heated beams

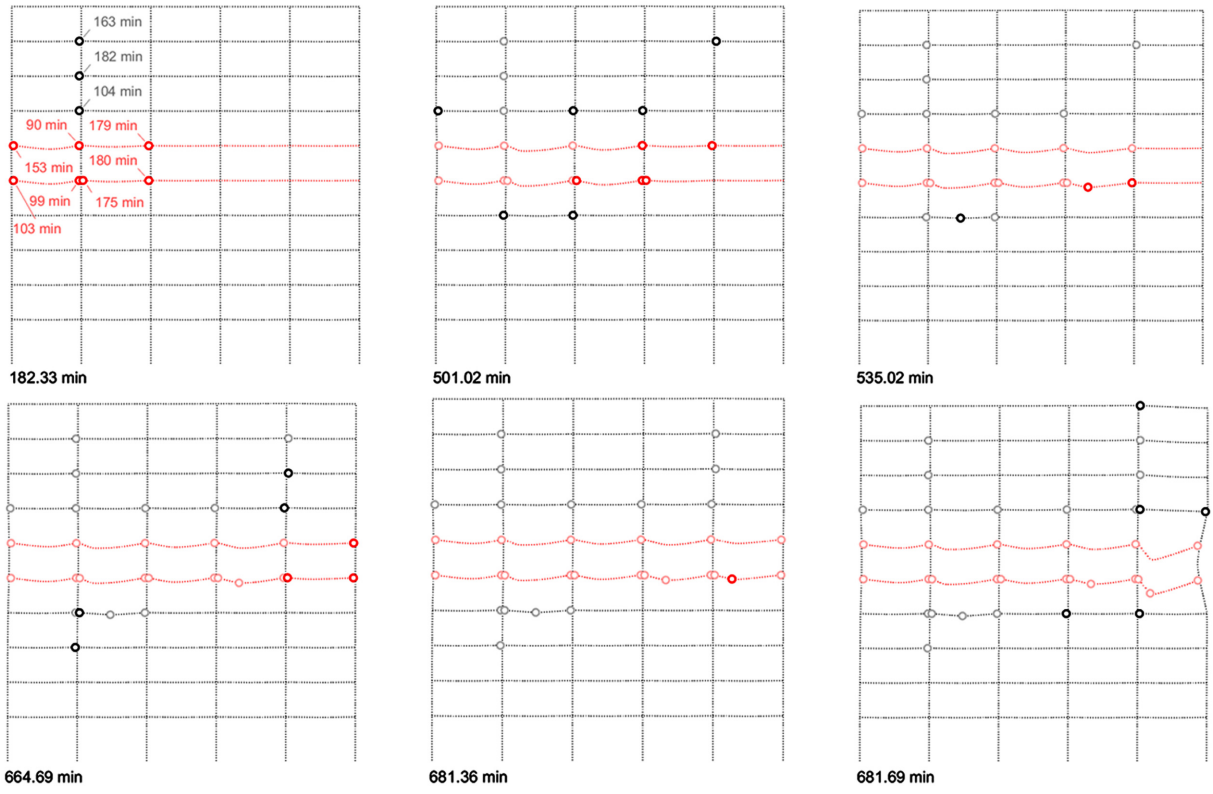


Figure 13. Deflected shape of the frame and formation of yielding points and plastic hinges (circles) at different times of fire exposure for a steel frame subjected to 2.5% TFM fire on 2-floors simultaneously. Red colour indicates the floor subjected to fire.

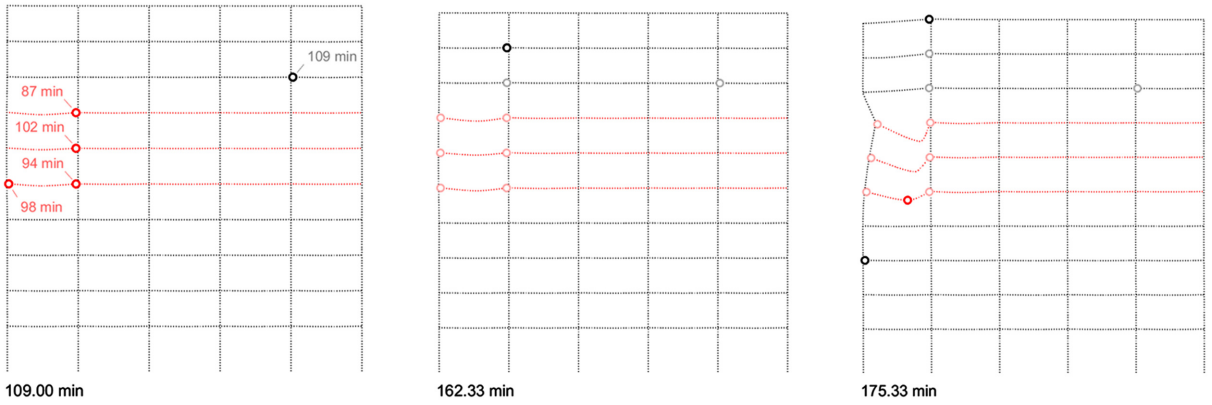


Figure 14. Deflected shape of the frame and formation of yielding points and plastic hinges (circles) at different times of fire exposure for a steel frame subjected to 2.5% TFM fire on 3-floors simultaneously. Red colour indicates the floor subjected to fire.

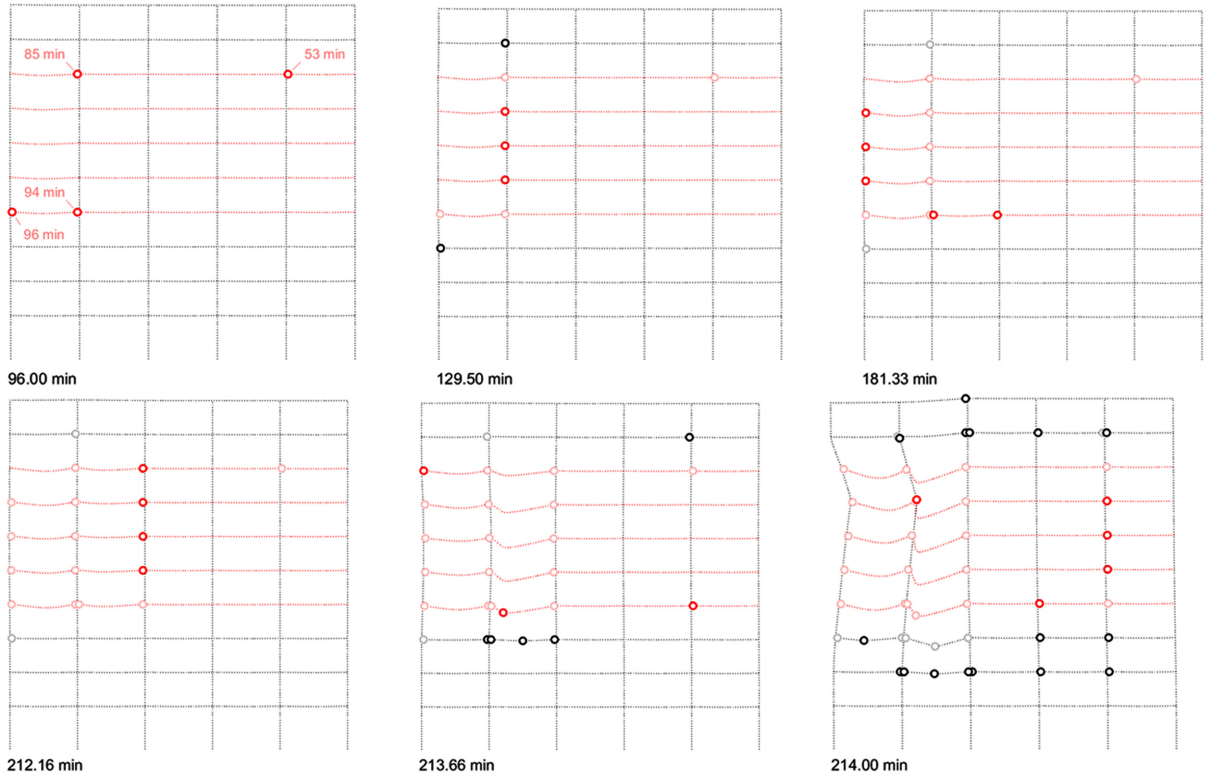


Figure 15. Deflected shape of the frame and formation of yielding points and plastic hinges (circles) at different times of fire exposure for a steel frame subjected to 2.5% TFM fire on 5-floors simultaneously. Red colour indicates the floor subjected to fire.

in Bay 1 causes a decrease in the bending moments and axial forces in those beams and increase in the bending moments in the cool floors (e.g. Floor #8) above. Collapse is initiated when fire reaches Bay 5 and the beams located in that bay go into catenary action pulling end columns (C6) inward. Plastic collapse mechanism forms once all the beams on the floor above the heated floors in Bay 5 have yielded. An increase in the bending moment in Bay 5 Floor #9 just before the mechanism forms and the beam yields can be seen in Figure 16.

For the cases when the frame is subjected to 2.5% TFM on more than 2 floors, collapse is initiated before fire reaches Bay 2 (3-floor and 7-floor fires) or Bay 3 (5-floor and 9-floor fires). It occurs after beams in Bay 1 yield and go into catenary action. The cumulative tensile axial force on heated columns C1 and redistributed forces in the floors above are large enough to cause yielding of the cool beams and, as a result, pull-in of the columns. For a

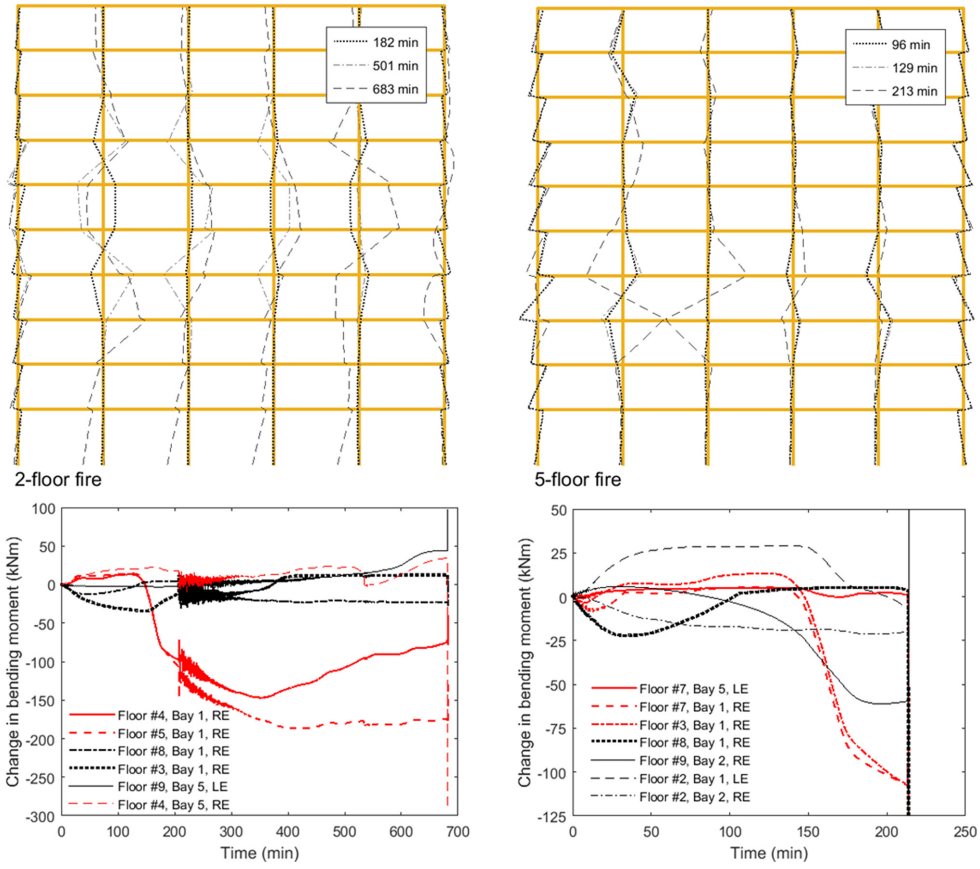


Figure 16. Generation of column (top) and beam (bottom) bending moments with time for selected structural members of the frame subjected to 2.5% TFM fire on 2-floors (left) and 5-floors(right). Red colour indicates the floor subjected to fire. RE and LE refer to right end, and left end of the beam, respectively.

3-floor fire plastic mechanism forms after all the beams in Bay 1 in the floors above the fire floor have yielded, while for a 5-floor fire it forms when beams below and above the heated floors in Bay 2 have yielded. In the latter case, as in all the other cases, before failure, forces are redistributed through cooler and stronger members. It can be observed by the formation of the plastic hinges in the cool floors and heated beams in Bay 5, which have not reached high temperatures yet (Figure 15). Loads are redistributed through the mechanism similar to the cantilever. For 7-floor and 9-floor fires, initiation of collapse is similar to 3-floor and 5-floor fires, respectively.

4.2.3. 10% TFM

The illustration of the deflected shape and the generation of plastic hinges with time for a steel frame exposed to

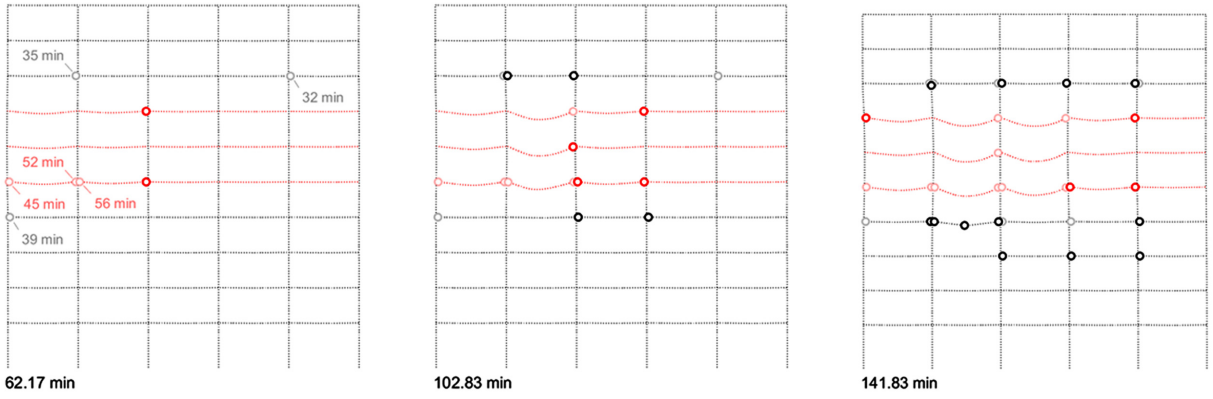


Figure 17. Deflected shape of the frame and formation of yielding points and plastic hinges (circles) at different times of fire exposure for a steel frame subjected to 10% TFM fire on 3-floors simultaneously. Red colour indicates the floor subjected to fire.

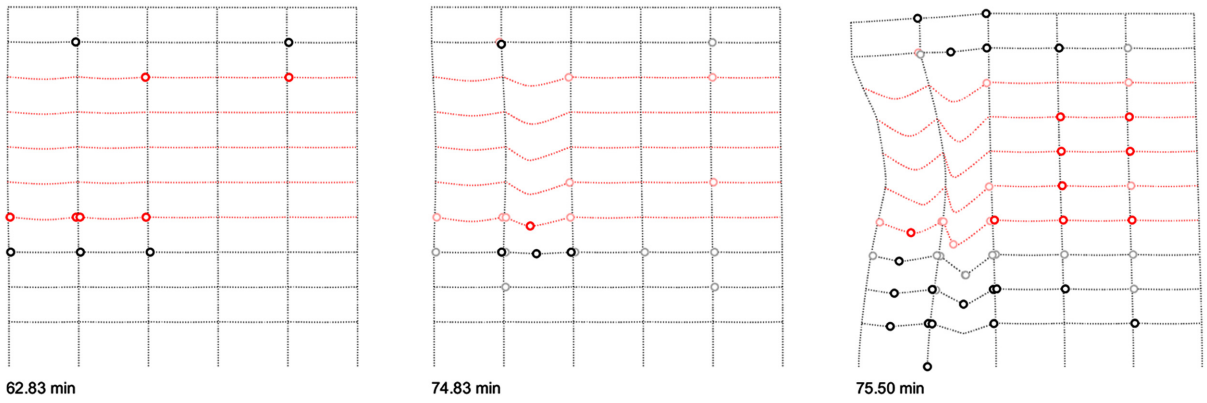


Figure 18. Deflected shape of the frame and formation of yielding points and plastic hinges (circles) at different times of fire exposure for a steel frame subjected to 10% TFM fire on 5-floors simultaneously. Red colour indicates the floor subjected to fire.

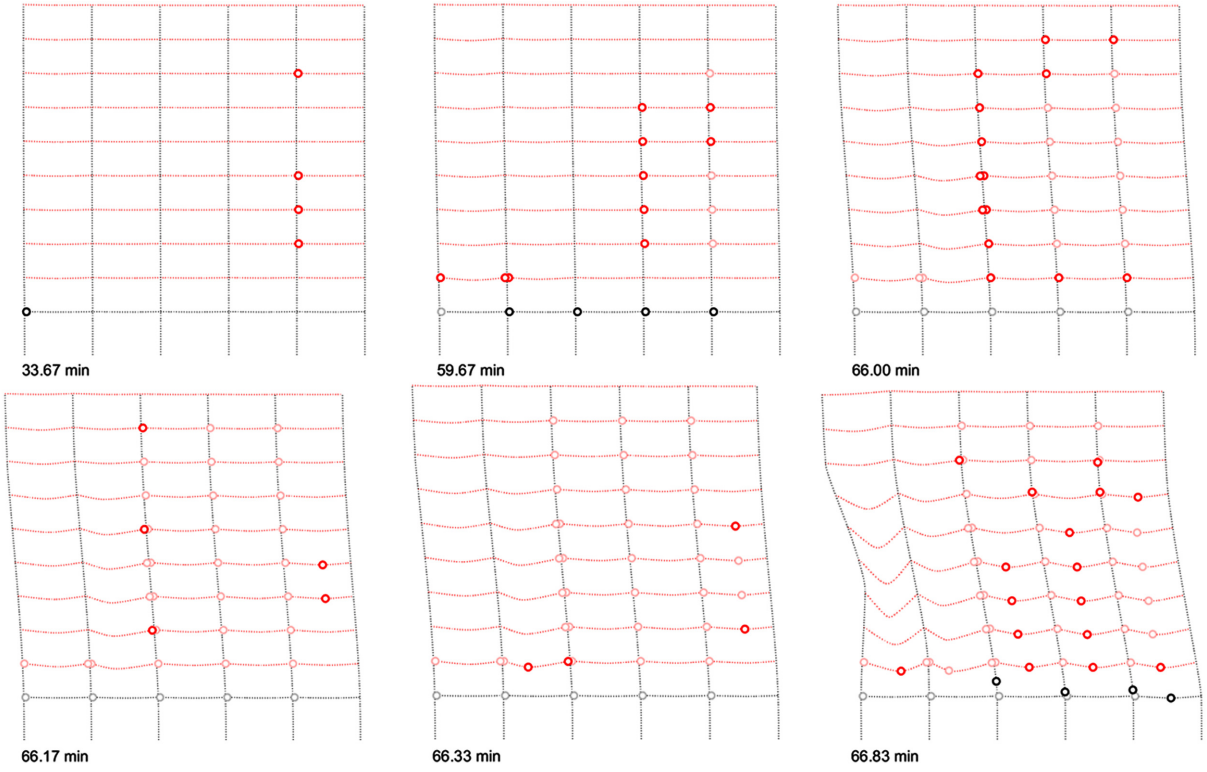


Figure 19. Deflected shape of the frame and formation of yielding points and plastic hinges (circles) at different times of fire exposure for a steel frame subjected to 10% TFM fire on 9-floors simultaneously. Red colour indicates the floor subjected to fire.

10%TFM fire on 3-floors, 5-floors, and 9-floors simultaneously is shown in Figure 17, Figure 18, and Figure 19, respectively. For 3-floor and 5-floor fires beams in Bays 1 and 2 in the lowest heated floors yield first followed by yielding of cool beams directly below or above the fire. However, initiation of collapse mechanisms for the two cases are different. For a 3-floor fire failure is initiated when fire reaches Bay 3 due to heated beam collapse whereas for a 5-floor fire failure is initiated by pull in of columns C1 and C2. In the former case, beam collapse in Bay 3 takes place after all the beams in the floors directly below and above the fire floors have yielded, tensile (catenary) axial forces have generated within the Bay 3 beams and ultimate strain failure has been reached. Redistribution of bending moments along the columns is illustrated in Figure 20. Initiation of collapse for a 5-floor fire is similar to the 2.5% TFM 5-floor fire discussed in a previous section. Collapse is initiated after beam collapse mechanism forms in Bay 2 Floor #2 and all the beams above the heated floors in Bay

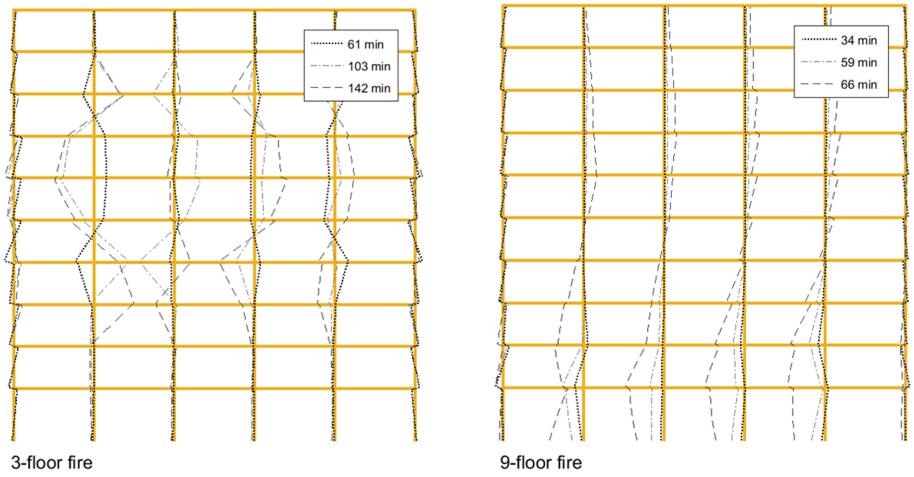


Figure 20. Generation of column bending moments with time of the frame subjected to 10% TFM fire on 3-floors (left) and 9-floors(right).

2 yield. This is similar to the weak-floor collapse mechanism reported in (Flint et al. 2007; Kotsovinos and Usmani 2013; Lange et al. 2012) in which collapse of the frame with long-span composite truss system occurs after buckling the cool floor directly below the fire floors.

Unlike in the previously discussed fire scenarios, collapse mechanism for a 9-floor fire is dominated by large deformations in the frame rather than loss of material strength. In this case, expanding beams on Floors #1 to #9 result in large cumulative lateral displacement of columns in Bays 1 and 2. In turn, additional bending moments are generated in Bays 5 followed by Bays 4 and 3 redistributing the load and maintaining stability of the frame. Yielding first occurs in the only cool floor, Floor #0, and Bay 5, where the highest forces are generated (see (Rackauskaite et al. 2017b) and Figure

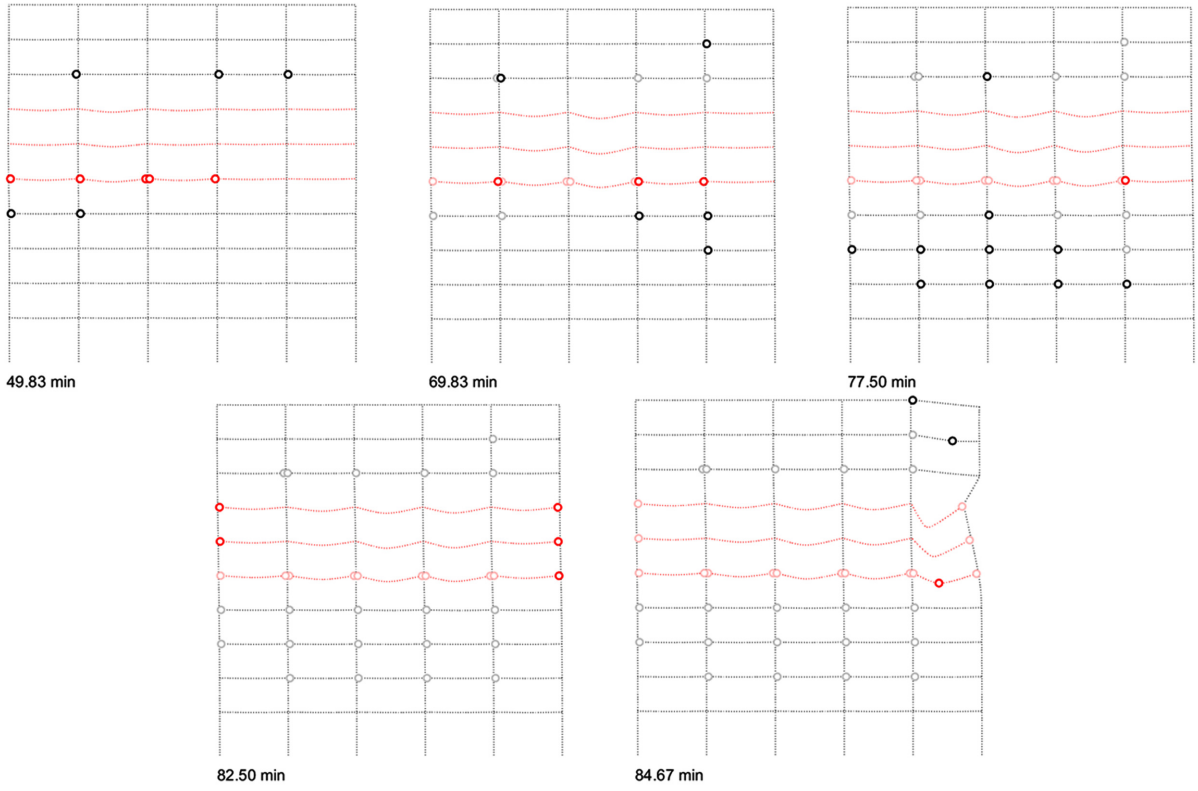


Figure 21. Deflected shape of the frame and formation of yielding points and plastic hinges (circles) at different times of fire exposure for a steel frame subjected to 25% TFM fire on 3-floors simultaneously. Red colour indicates the floor subjected to fire.

20). Frame begins to collapse by swaying to the side of the fire origin after all most of the beams in Bays 3 to 5 and columns C3 to C5 on Floor #1 have yielded forming a plastic collapse mechanism. Frame is no longer able to transfer the load to stronger members and maintain stability. For 2-floor, 7-floor, and 10-floor fires, initiation of collapse is similar to 3-floor, 5-floor, and 9-floor fires, respectively.

4.2.4. 25% TFM

The illustration of the deflected shape and the generation of plastic hinges with time for a steel frame exposed to 25% TFM fire on 3-floors, 5-floors, and 9-floors simultaneously is shown in Figure 21, Figure 22, and Figure 23, respectively. As in previously discussed cases, yielding occurs first in the beams on the lowest heated floor and cool floors directly above and below the fire floors in Bay 1. This is due to the forces generated as a result of the restrained thermal expansion. For a 3-floor fire, only the beams on the lowest fire floor yield as the fire travels across the compartment. Fire generated forces are redistributed to the cool floors above and below the fire floor. The extent of the yielded unheated members below the fire floors is higher than for a frame subjected to 2.5% TFM and 10% TFM. This is mainly because collapse is initiated towards the end of fire exposure unlike in the latter cases. 25% TFM fire travels faster across the compartment. Initiation of collapse for a 3-floor fire occurs when the heated beam in Bay 5 Floor #4 goes into catenary action and beam in Bay 5 Floor #9 yields forming a plastic collapse mechanism. Redistribution in bending moments in columns and beams in illustrated in Figure 24.

5-floor and 9-floor initiation of collapse mechanisms are similar. Beams on the fire affected floors expand pushing columns in Bay 1 outward. Significant cumulative column lateral displacement develops due to the heating of a large number of fire floors (more than 3). This creates a large momentum in the frame generating additional forces in Bay 5 and causing yielding. Therefore, as for the 10% 9-floor fire failure is dominated by large deformations. For a 5-floor fire, frame is unable to maintain stability after all the beams in floors below the fire and heated beams in Bay 5 have yielded. For a 9-floor fire collapse is initiated after yielding of the unheated beams on Floor #0 and heated beams in Bays 3 to 5. It is similar to the collapse mechanism of a frame exposed to a 10% TFM on 9 floors. Figure 24 shows increasing bending moments in Bay 5 to Bay 3 beams as fire spreads along the compartment and generation of high bending moments along the internal columns for a 9-floor fire as the frame begins to sway. For 2-floor, 7-floor, and 10-floor fires, initiation of collapse is similar to 3-floor, 5-floor, and 9-floor fires, respectively. Comparison of effects of the

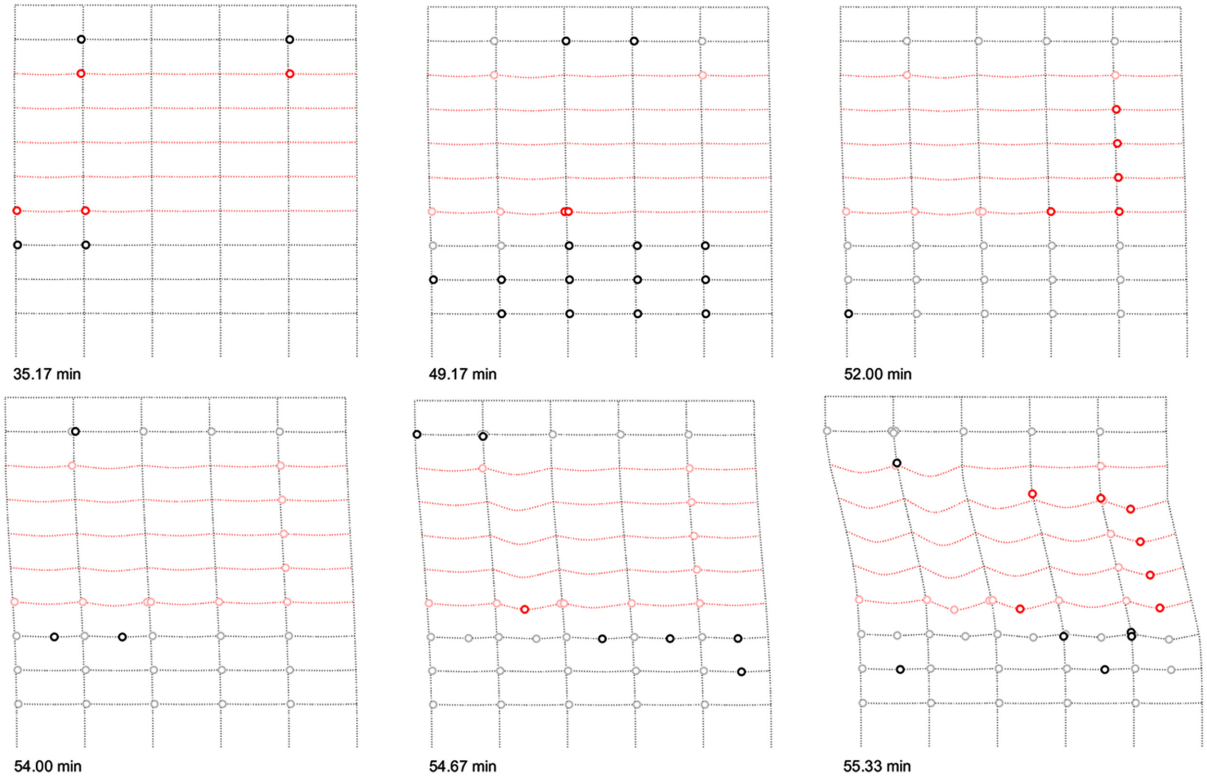


Figure 22. Deflected shape of the frame and formation of yielding points and plastic hinges (circles) at different times of fire exposure for a steel frame subjected to 25% TFM fire on 5-floors simultaneously. Red colour indicates the floor subjected to fire.

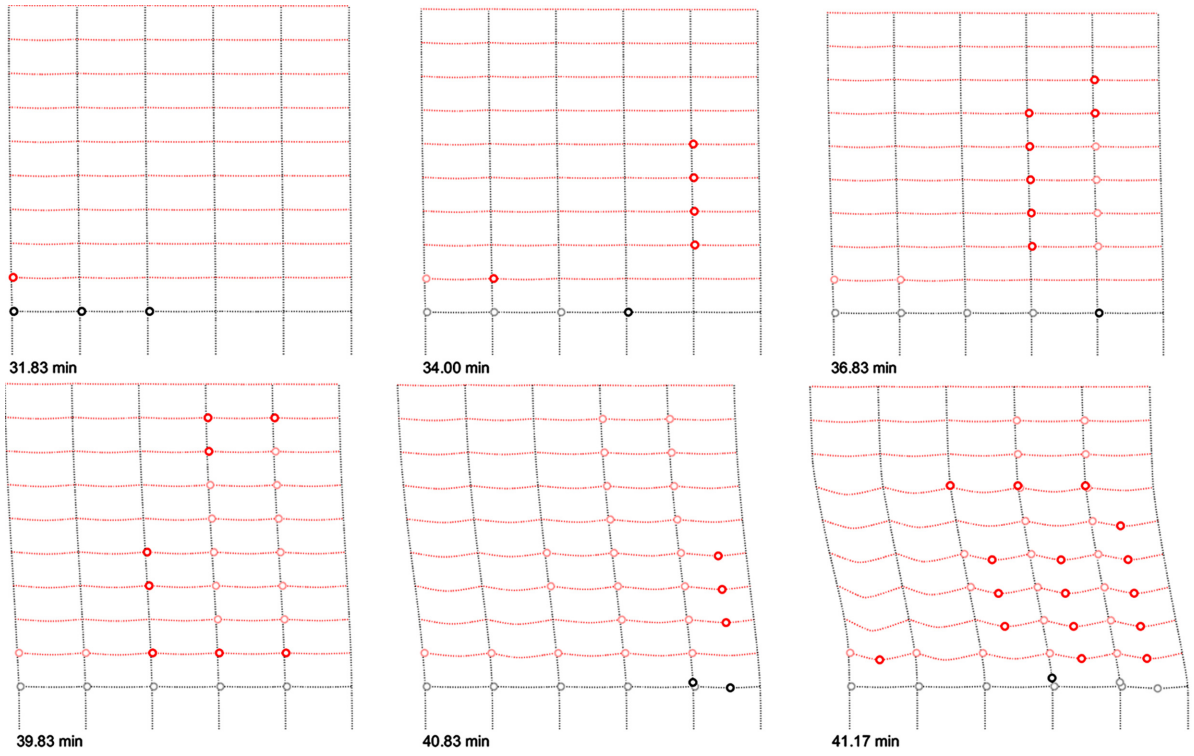


Figure 23. Deflected shape of the frame and formation of yielding points and plastic hinges (circles) at different times of fire exposure for a steel frame subjected to 25% TFM fire on 9-floors simultaneously. Red colour indicates the floor subjected to fire.

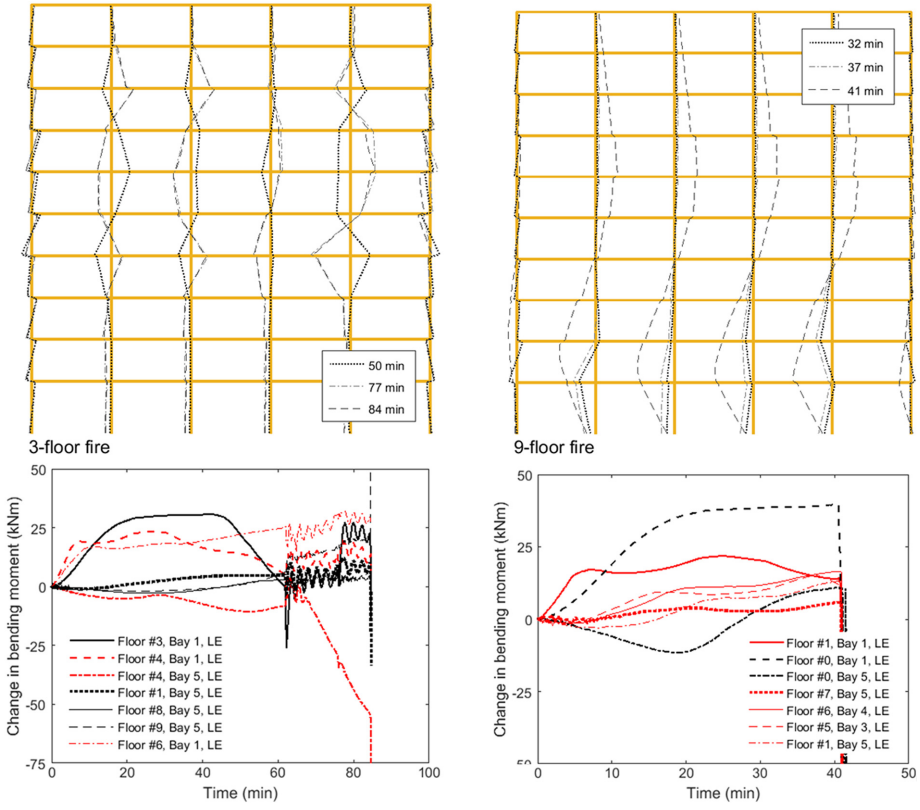


Figure 24. Generation of column (top) and beam (bottom) bending moments with time for selected structural members of the frame subjected to 25% TFM fire on 3-floors (left) and 9-floors (right). Red colour indicates the floor subjected to fire. RE and LE refer to right end, and left end of the beam, respectively.

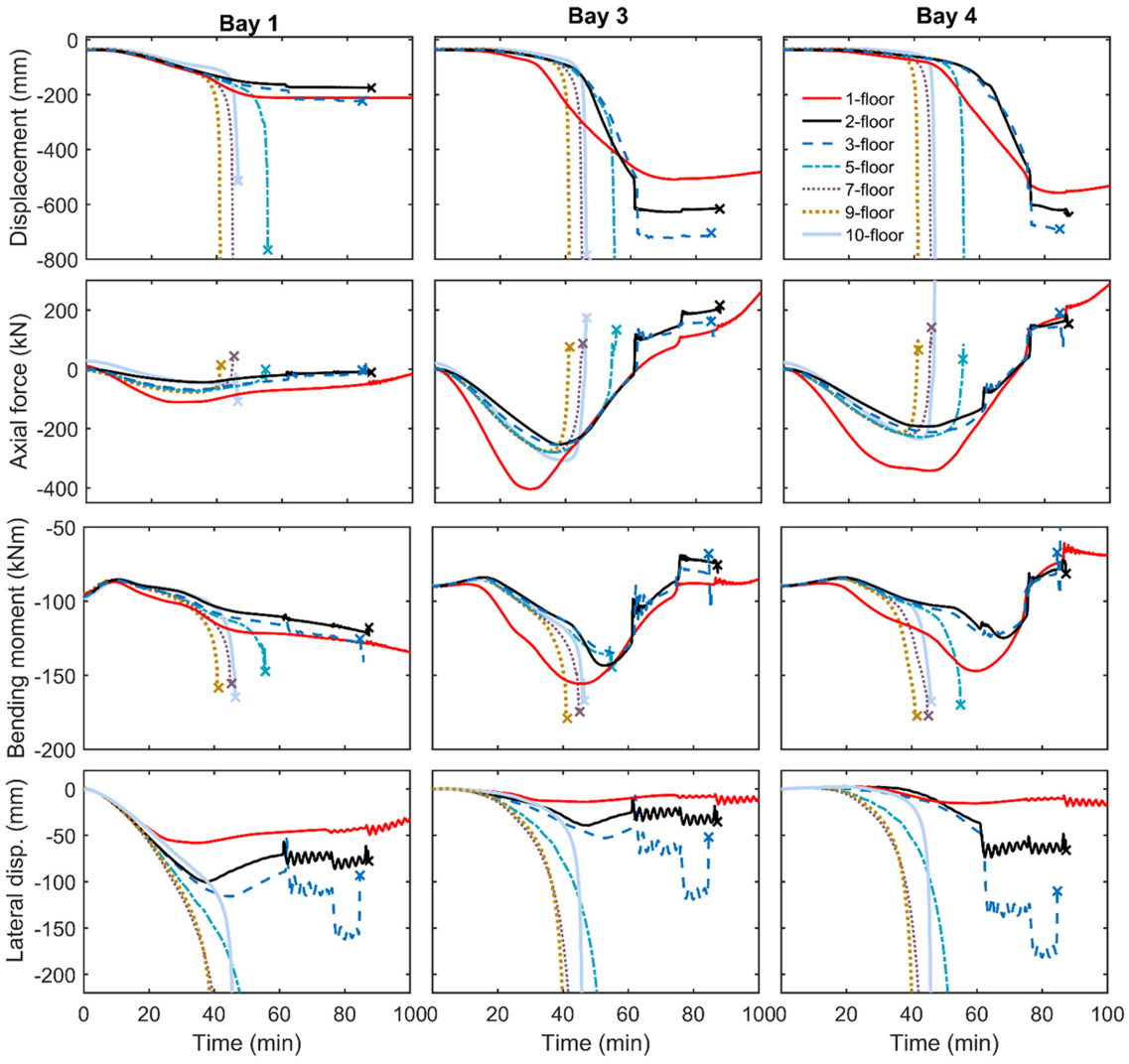


Figure 25. Development in time of mid-span deflections, axial forces, and bending moments at each of the beams in the lowest heated floor; and development of lateral displacements at the beam to column nodes on the left hand side of the beam for a varying number of multiple fire floors. Frame is subjected to the 25% TFM.

changing number of fire floors on the development of stresses and displacements is illustrated in Figure 25. Results are illustrated for beams in Bay 1, Bay 3 and Bay 4 for 1-floor to 10-floor fires. The highest axial forces and bending moments within heated beams are generated when the frame is subjected to the 25% TFM on 1 floor. This is because beams are axially restrained by columns in the cool floors directly above and below the fire floor and, therefore, differential lateral elongation between beams in the adjacent floors is the largest in comparison to larger number of fire floors. Figure 25 shows, as identified previously, the increasing lateral displacement of columns towards the side of fire origin and increasing bending moments with increasing number of simultaneously heated fire floors.

Figure 26 and Figure 27 show the deflected shape and the generation of plastic hinges with time for a steel frame exposed to 48% TFM fire on 5-floors, and 9-floors simultaneously, respectively. The mechanism of collapse is similar to the frame exposed to 25% TFM on 5 floors and 9 floors. It occurs due to large deformations within the frame, i.e. cumulative lateral displacements of columns, which are being pushed by expanding beams, in Bays 1 and 2. This results in the generation of large bending moments within the frame, particularly in unheated floors Floor #0 to Floor #2 (3-floor fire) and Floor#0 (9-floor fire) before the initiation of collapse (see Figure 28). Instability and failure takes place when the frame is no longer able to redistribute the forces. For a 5-floor fire stability is mainly maintained by the cool floors below the fire floors and after beams within these floors have yielded frame begins to sway. For a 9-floor fire stability is maintained and loads are redistributed through the beams and columns in Bay 5 followed by Bays 4 and 3 after the unheated beams in Floor #0 have yielded. For 7-floor, and 10-floor fires, initiation of collapse is similar to

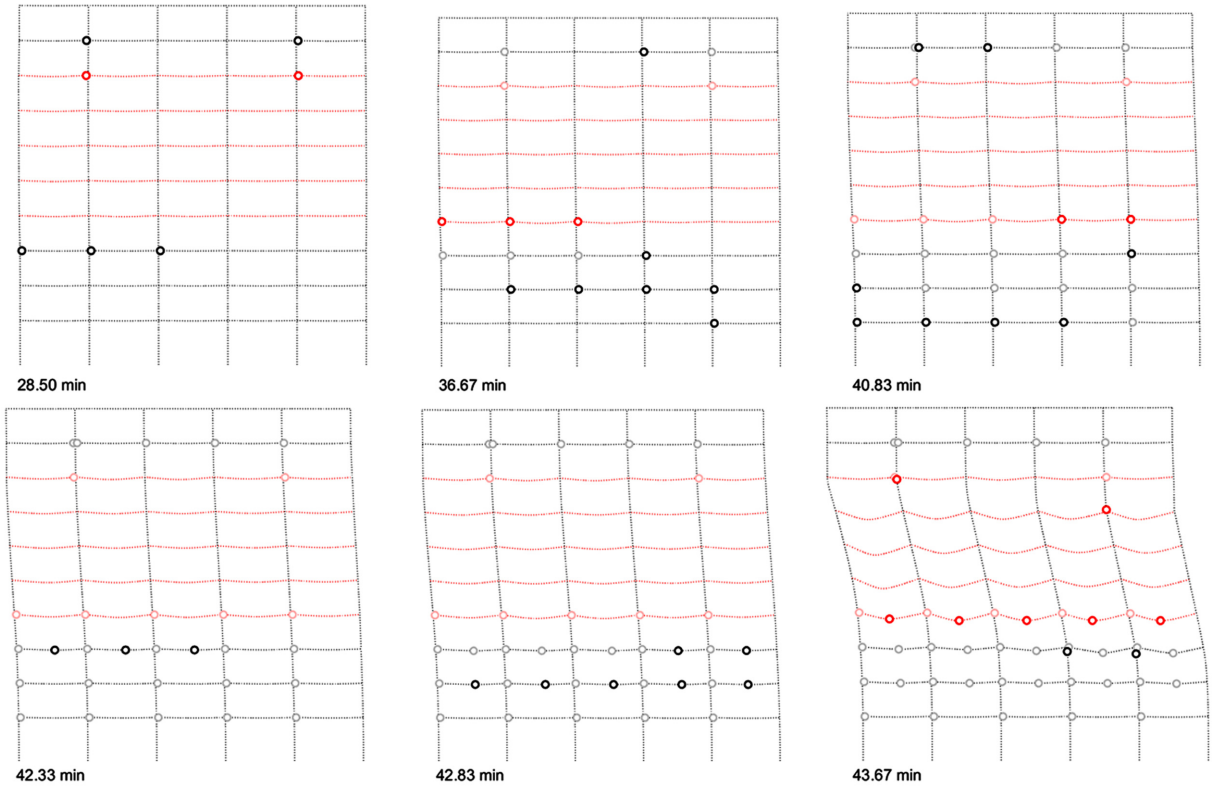


Figure 26. Deflected shape of the frame and formation of yielding points and plastic hinges (circles) at different times of fire exposure for a steel frame subjected to 48% TFM fire on 5-floors simultaneously. Red colour indicates the floor subjected to fire.

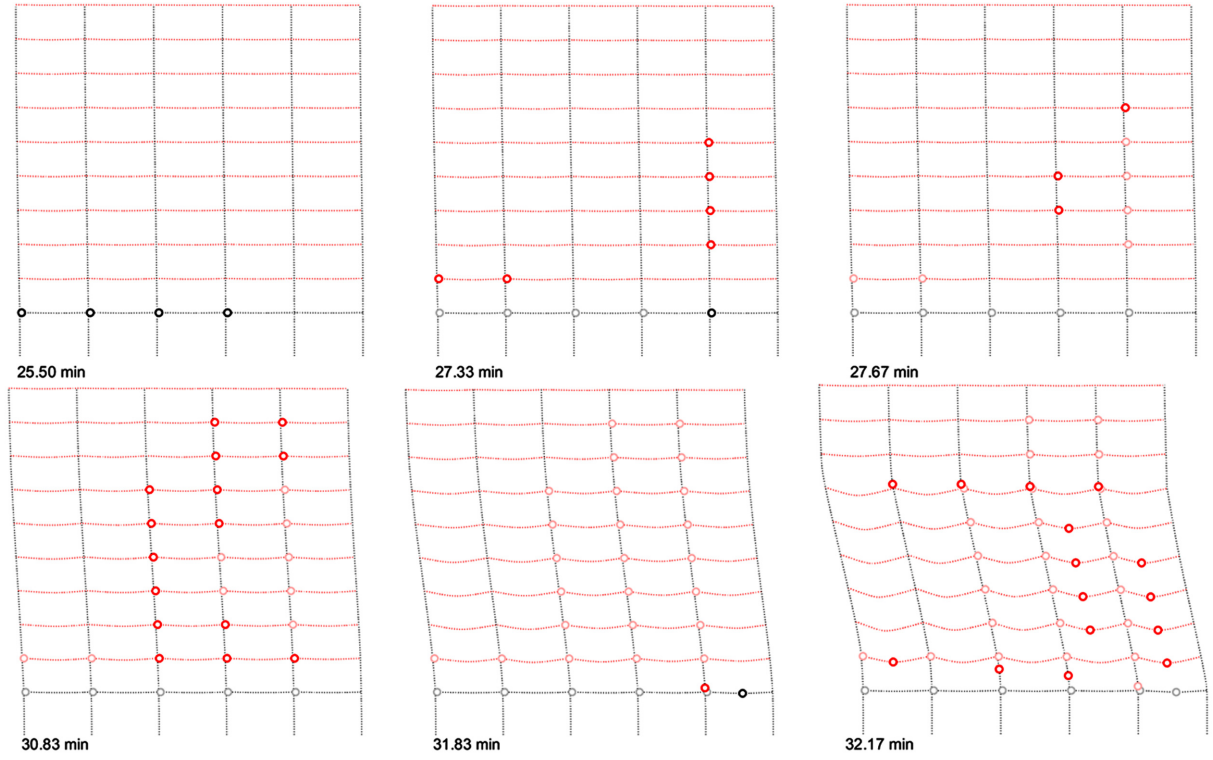


Figure 27. Deflected shape of the frame and formation of yielding points and plastic hinges (circles) at different times of fire exposure for a steel frame subjected to 48% TFM fire on 9-floors simultaneously. Red colour indicates the floor subjected to fire.

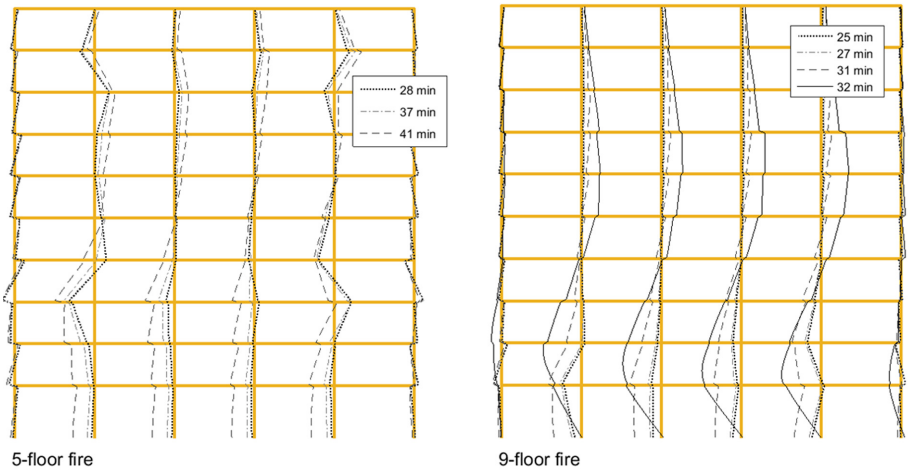


Figure 28. Generation of column bending moments with time of the frame subjected to 48% TFM fire on 5-floors (left) and 9-floors. (right)

5-floor, and 9-floor fires, respectively.

5. Conclusions

In this paper, 58 different cases of a generic steel frame subjected to horizontally and vertically travelling uniform and travelling fires were analysed in LS-DYNA to investigate collapse initiation and mechanisms. The frame examined has a simple and generic structural arrangement and higher applied fire protection to the columns compared with the beams. The conclusions from this case study are limited to structures with similar characteristics. A 2D analysis has been undertaken and, therefore, the tensile membrane action of the slab has not been considered and a 3D analysis could be undertaken in the future to explore this particular limitation.

In most of the analysed cases yielding first occurs in the lowest and highest fire floors and adjacent cool floors close to the connections. This is because the highest axial forces and bending moments due to the restrained thermal expansion are generated within these floors. For uniform fires, beams in the central bay yield first followed by Bays 2 & 4 and Bays 1 & 5, while for travelling fire scenarios yielding of the beams on the heated floors follows the fire spread. Buckling of the columns does not occur in any of the cases likely because they were assumed to have a higher level of protection than beams (i.e. equivalent to 120 min of standard fire exposure). Therefore, columns do not reach sufficiently high temperatures to cause significant thermal expansion and additional axial forces, which could lead to buckling. The current analysis does not consider the potential for squashing of the column head as it was observed in the Cardington tests although this would be unlikely to lead to building collapse. In addition, the utilization of the columns at ambient temperature is significantly lower than the utilization of beams (by up to 40%). Thus, failure for the frame considered in this study is mainly governed by the thermally induced loads generated as a result of the restrained thermal expansion of the beams as in (Becker 2002; Flint et al. 2007; Kilic and Selamet 2013).

For single floor fires, initiation of collapse mechanisms could be split into two general groups depending on the location of the fire floor of the frame. In the first group (*Group S*1), collapse is initiated by the pull-in of external columns after heated beams in Bays 1 & 5 (uniform fires) or Bay 5 (travelling fires) go into catenary action. This occurs for fires located in the upper floors of the frame (uniform fires Floors #6-#9 and travelling fires Floors #5-#9). Heated beams on the upper floors are connected to the weaker column sections than in the lower floors and they are unable to transfer and sustain the loads after beams in end bays go into catenary action. In the second group (*Group S*2), i.e. fires occurring on the lower floors of the frame, the frame is sufficiently robust to resist the catenary action and maintain stability. In these cases, failure is initiated (i.e. ultimate strain of the material is exceeded) after the local beam collapse. Failure in both groups is governed by the generation of high loads due to restrained thermal expansion and the loss of material strength.

For multiple floor fires, different fire scenarios can also be split into two main groups. In the first group (*Group M* 1), failure is mostly dominated by the loss of material strength and occurs for the cases with 1 to 3 fire floors and all 2.5% TFM and ISO scenarios. Similarly to group 1 for single floor fires, collapse is initiated by the pull-in of external columns at the fire origin (Bay 1) or towards the end of the fire path (Bay 5). In the second group(*Group M*2), failure is dominated by the thermal expansion and geometric effects and collapse is initiated by swaying of the frame to the side of the fire origin. It occurs for the cases with 5 or more fire floors. Moreover, for the 3-floor 10% TFM and 5-floor 2.5% TFM results

in Bay 2 indicate deflected shape patterns similar to the weak-floor collapse reported in (Flint et al. 2007; Lange et al. 2012; Liew et al. 1998). In the other scenarios deflection patterns and pull-in of the columns is similar to the strong-floor or a mixed collapse mechanism. However, it should be noted that the location of multiple floor fires was not varied in this study. Location of multiple floor fires in the frame could have a significant affect on the collapse mechanism (as for single floor fires) and needs further investigation.

The results indicate that for the investigated frame initiation of collapse mechanisms are affected not only by the fire type but also the number of fire floors and location of the fire floor. The finding of this study could be of use to designers of buildings when developing fire protection strategies or when assessing the initiation of collapse for steel framed buildings.

6. Acknowledgments

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