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INTEGRATED ANALYSIS OF LOADING ECCENTRICITY ON RESPONSE OF A COLUMN UNDER TRAVELLING FIRE

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ABSTRACT

Columns are crucial structural elements designed to carry axial loads. When these loads are applied off the column's central axis, it results in eccentric loading, introducing both axial stress and bending moments in the column. This complexity becomes even more pronounced under transient heating conditions, such as those encountered during travelling fires. Understanding these interactions is vital for designing structures that can withstand unusual loading and heating scenarios, ensuring their safety and resilience. In consideration of this, the present study undertakes nonlinear analyses to explore the effects of eccentricities due to load positioning and also the effects of transient heating on columns and beams exposed to traveling fires. The analysis is conducted in two phases: initially, an isolated steel column is subjected to full-scale traveling fires, considering axial loading with eccentricity ratios (e/h) of 0, 0.25, and 0.5. Subsequently, a two-bay frame is exposed to the combined effects of traveling fires and imposed loads. The computational modelling for this investigation is done using Abaqus software. Findings from the analysis reveal that increased eccentricity significantly enhances lateral deformation and triggers local buckling in flanges. Columns under higher eccentricity also display lower temperatures at which buckling occurs. Additionally, for steel frames, the combination of transient heating and imposed loads brings about both axial and flexural deformations in structural members. As eccentricity escalates, there's a notable reduction in critical load, precipitating premature section failure and significant lateral displacement. Furthermore, critical stresses are observed at beam-column junctions, and a twisting phenomenon occurs when beams are subjected to transient heating while columns remain at ambient temperatures.

Keywords: Travelling Fires; Steel Columns; Fire Resistance; Computational modelling

1 INTRODUCTION

The ability of buildings to withstand fire is crucial for the safety, and well-being of the occupants and the protection of the building's contents. Due to large open-plan layouts in modern building designs, one of the most challenging scenarios for building safety is a travelling fire. During travelling fires, structural elements are exposed to a complex thermal environment and high temperatures for prolonged durations. Such fire exposures may compromise the integrity of the structure leading to failure [1-2]. In structural fire design, the standard fire exposure conditions (ISO-834) are considered which assume a post-flashover fire scenario with uniform temperatures within the compartment. This assumption may stand true for small compartments, however, for larger floor areas, the assumption of uniform temperatures within compartments has been found to be inaccurate [3-4]. Since the beginning of the century, there have been

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several well-documented cases of traveling fire incidents, including the 2001 World Trade Center Twin Towers in New York City, the 2005 Windsor Tower in Madrid, and the 2008 Faculty of Architecture Building at Delft University of Technology in the Netherlands [6-7]. In terms of fire incidents in the UK, the tragic Grenfell Tower fire incident in London in 2017 remains one of the most recent and impactful fire incidents in the country [8]. These large fire incidents have attracted the interest of researchers from different parts of the world to study large open plan fires and their impact on the surrounding structural frames during such fires. Generally, the response of structural elements is temperature dependent as their strength and stiffness are compromised at higher temperatures. In case of fire exposure, the structural elements may achieve temperatures as high as 1000°C which significantly reduces their resistance to external loads. Two main factors impact the mechanical properties of structures during a fire: a) thermal elongation and b) the decrease in modulus of elasticity and yield strength of materials. The thermal elongation results in the generation of compressive forces within the structural members due to the restraining effect from the surrounding structure which may lead to the buckling of the structural member [9]. Furthermore, the decrease in modulus of elasticity and yield strength of materials due to fire exposure leads to strength loss and has profound consequences on the safety, integrity, and functionality of structures.

In any structural skeleton, a column is a fundamental element and plays a critical role in the overall resistance, support, stability, and integrity of buildings. The importance of columns is magnified when they are directly influenced by the fire dynamics often being engulfed in flames [10]. When a steel column in a building is exposed to fire, several consequences can occur including thermal expansion leading to distortion and potential buckling. In addition, the combination of axial load, eccentricity (e), and high temperatures can elevate the risk of buckling in the column. This introduces higher bending stress, lateral-torsional buckling, P-Delta effect, and causes a reduction in the effective area of the column [11]. This phenomenon can be observed in travelling fires even for centric loads due to transient heating of the structure. For instance, the position of the travelling fire at a point may compromise the strength of the nearby structural elements, including the columns. On the other hand, the structural elements away from the travelling fire will still offer support and resistance to the external loads. The beams supported on the hotter side transfer loads to the column in a different way as compared to the beams supported on the cooler side. This temperature difference in the beams creates eccentricity in the column which is encountered during a travelling fire event (or in a large compartment fire event) and is irrelevant to the loading conditions of the column.

Yao et al., [12] conducted a computational analysis to assess the behaviour of concrete-filled steel tubular (CFST) slender columns subjected to eccentric loads and exposed to ISO-834 standard fire. Their model incorporated parameters like concrete tensile strength and stirrup ratio which yielded reasonable accuracy compared to experimental results. The computational modelling approach was further used to conduct parametric studies to investigate the impact of various factors such as eccentricity ratio, yield strength of steel, compressive strength of concrete, and the reinforcement ratio on the fire resistance of CFST columns. In another study, Du et al., [13] investigated the behaviour of eccentrically loaded pin-ended concrete-encased steel (CES) composite columns under heating and cooling conditions. Du et al (2013) [13] developed and validated a nonlinear 3D finite element analysis (FEA) model using ANSYS. The findings from their study revealed that CES columns undergo temperature increases at different rates and positions, emphasizing the need to consider full fire exposure until temperatures decrease uniformly. They observed significant lateral deformation during the cooling phase. Detailed FEA studies by Du et al (2013) identified key parameters such as load ratio, slenderness ratio, duration time, depth to width ratio, and steel ratio influencing lateral deformation and residual deformation ratio, providing insights for structural design considerations. An experimental study conducted by Al-Talqani et al.,[14] examined the response of normal-weight concrete encased steel (CES) columns under eccentric loading and varying elevated temperatures, using an electrical furnace. The findings from the experiments demonstrated that all CES columns experienced failure due to flexural buckling, with concrete crushing occurring at the middle third of the compression side of the column, accompanied by local buckling of the steel section flange.

The existing literature [15–18] predominantly focuses on concrete columns under eccentric loading during standard fire conditions, with limited attention given to steel columns subjected to eccentric loading due to traveling fire scenarios. Understanding the behaviour of eccentrically loaded columns under traveling fire conditions is crucial for ensuring structural safety considering modern designs and open-plan layouts. To understand the influence of temperature-induced eccentricities, it is vital to initially study the response of eccentrically loaded columns in travelling fires. The combination of non-uniform temperature and loading eccentricity could profoundly impact the behaviour of columns, a scenario that has not yet been explored in detail as evident from the existing literature. The integrated analysis presented in this study provides valuable insights into the response of columns, aiding in achieving better design and fire-resistant construction practices.

2 NUMERICAL ANALYSIS

Computational analysis during this research is conducted using ABAQUS software [19], a robust tool renowned for finite element analyses and computer-aided engineering tasks. The numerical analysis encompasses two phases. During the initial phase, the first eigenmode is determined through a linear perturbation frequency analysis procedure. This eigenmode is subsequently utilized in the stress analysis phase (the second phase) to induce the necessary initial imperfection of the column set as L/1000 in all cases [20]. In the stress analysis phase, the column is partitioned into five levels, as illustrated in Figure 2, with temperatures applied through predefined fields. For structural investigation, a distinct set of analysis elements are employed for steel. The steel material is modelled using incompatible mode elements, specifically C3D8I elements, as done previously by other researchers while performing computational modelling on steel structures [21]. The 40 mm average element size mesh was compatible with the procedures in all cases. The mechanical properties of materials during structural analysis have also been taken from the Eurocodes [22].

2.1 Validation with experimental data

To confirm the accuracy of the FE analysis method, the numerical predictions were compared with the key results from experiments conducted by Faris and Conner [23] on axially loaded restrained columns. The details of the experiment are reported in the publication listed as reference [23]. The numerical predictions were compared with the key results from experiments which included the axial deformation and lateral displacement in a column. The numerical findings exhibited a notable concurrence with the experimental outcomes. In this study, both dynamic explicit and nonlinear static analyses were executed to validate the method's accuracy, yielding consistent results across both approaches. To mitigate computational expenses and keeping in view the scope of this paper, the static analysis is considered to simulate the column behaviour under prescribed loads subjected to a traveling fire. The results of axial and lateral displacements are shown in Figure 1.

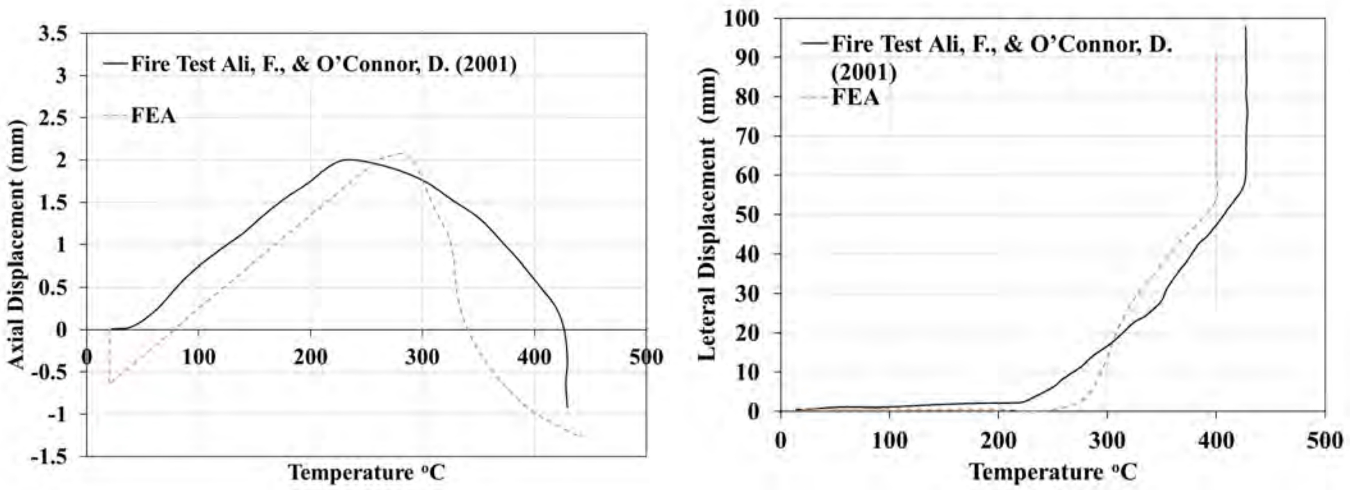

Figure 1. Axial and lateral deformation

3 CASE STUDIES

3.1 Investigated Cases

The methodology consisted of computational analysis conducted in two phases as explained above. The computational analysis is initially performed for isolated HEA200 steel columns subjected to travelling fires. The selected column sections are the same as the ones used during the tests performed at Ulster University [1, 24]. The columns were subjected to axial loading with consideration for the following eccentricity cases: 1) e/h = 0, 2) e/h = 0.25, and 3) e/h = 0.5, as illustrated in Figure 2. In these cases, "e" represents the eccentricity, and "h" denotes the depth of the section. The variations in loading eccentricity were applied along the minor axis on the web of the section. The imposed load on the column in this case is 50% of the minimum design buckling resistance ($N_{b,rd}$) of a column section about minor axes.

In the second phase, eccentricity was induced through the transient heating of structures. For example, as illustrated in Figure 2(b), a section of the frame was exposed to fire, potentially compromising the strength of elements, reducing stiffness, and altering the load transfer path compared to the sections at ambient temperatures. This induced eccentricity in the column, regardless of any variations in eccentricities induced due to the position of the external loads applied. In the second phase, four distinct scenarios as listed in Table 1. In case 1, only the column is subjected to transient heating while in case 2, along the column, one beam is also exposed to elevated temperatures as seen in Figure 2(b). In cases 3 and 4, additional loads of 20% and 30% are applied, respectively, based on the load-carrying capacity of the beam (see Table 1). *Note. In the text thermal load, temperature load, and transient heating refer to travelling fire scenarios*.

Table 1: Details of frame cases selected for computational investigation

Frame Cases	Details
Case 1	Only middle column exposed to travelling fire.
Case 2	Middle column and one beam exposed to travelling fire (see Figure 2(b)).
Case 3	Same as Case 2 but with 20% external loads.
Case 4	Same as Case 3 but with 20% external loads.

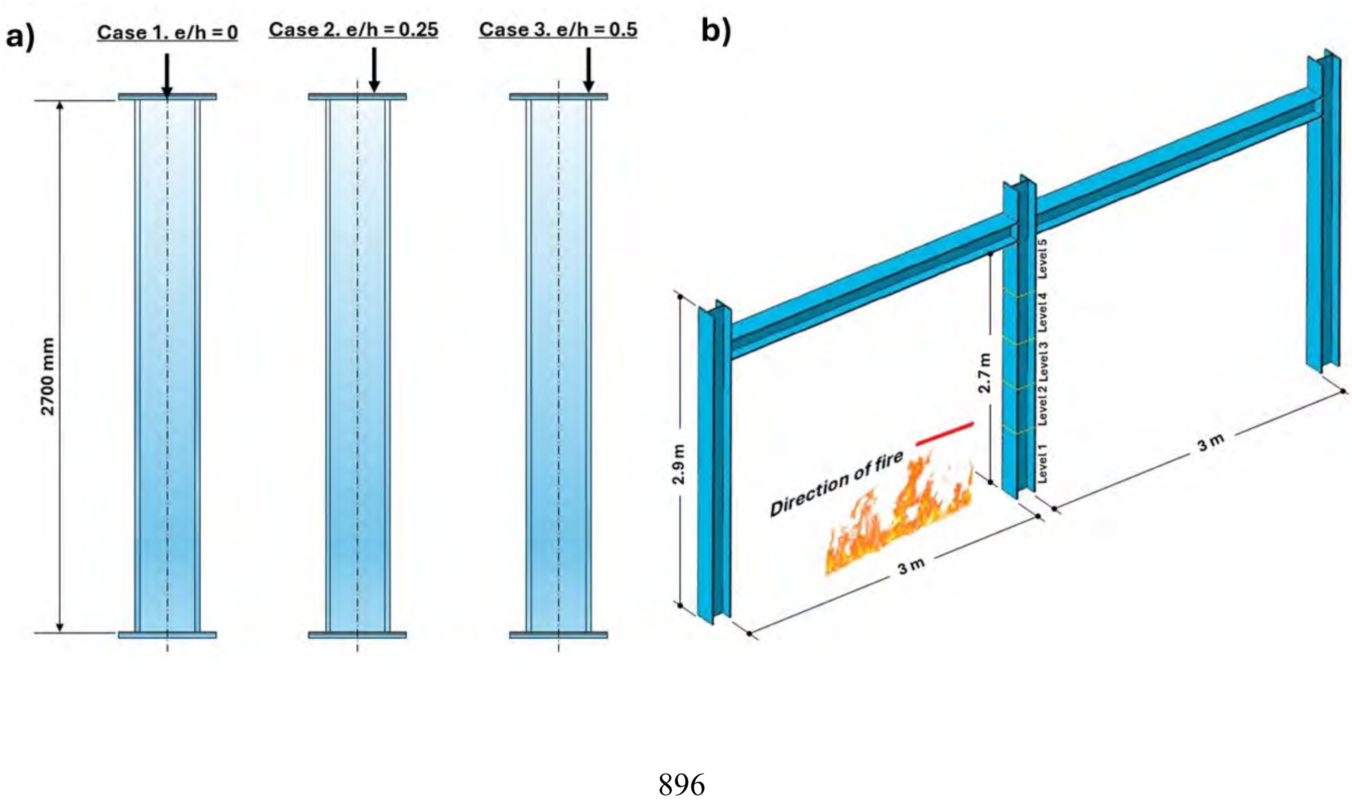

Figure 2. a) Analysis phase I, eccentricity scenarios with respect to axial loads, b) Analysis phase II, eccentricity scenarios according to transient heating (the travelling fires)

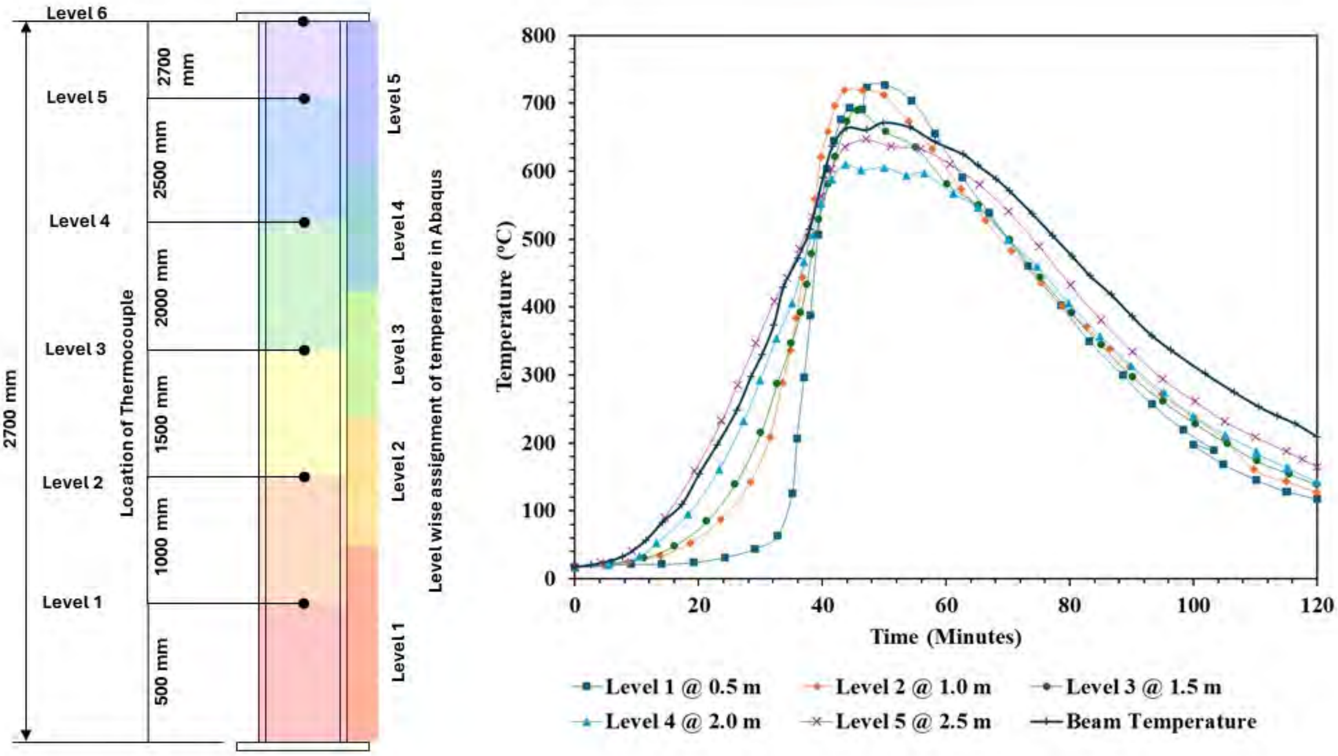

Figure 3. Recorded temperature in columns at different levels extracted from [2]

4 RESULTS

4.1 Column under travelling fire scenario

Since no external loading was considered in the real fire test [2], initially, the computational simulation of the model was exclusively under thermal loading considering the temperature data obtained for the test, with no external loads to evaluate deformations. The boundary conditions at the column's base were set as fixed while allowing translational movement in the vertical direction and rotational movement about the z and x axes at the top of the column. The results describing displacements of the column under thermal loading along all three axes are illustrated in Figure 4.

The displacements are measured at various levels in all three directions due to the temperature being applied incrementally across levels as shown in Figure 3. The deformation along the x, y, and z axes are shown as U1, U2 and U3 respectively in Figure 4. Notably, Figure 4 reveals that the maximum displacement occurs in the vertical direction (U2), which defines axial displacement, whereas displacements in the other two directions (U1 and U3) are observed to be negligible. As the temperature was applied transiently, upon reaching maximum temperature, the deformation peaks; correspondingly, as the temperature decreases, the deformation reduces. Specifically, the maximum axial deformation of 23 mm is observed at the top level of the column during peak temperature. Subsequent cooling results in reduced deformation, with the residual deformation in the column recorded at 5 mm. Overall, no severe deformation is observed as per the results. This was also observed during the full-scale experiments by Ulster University as no damages were reported during the fire test [2].

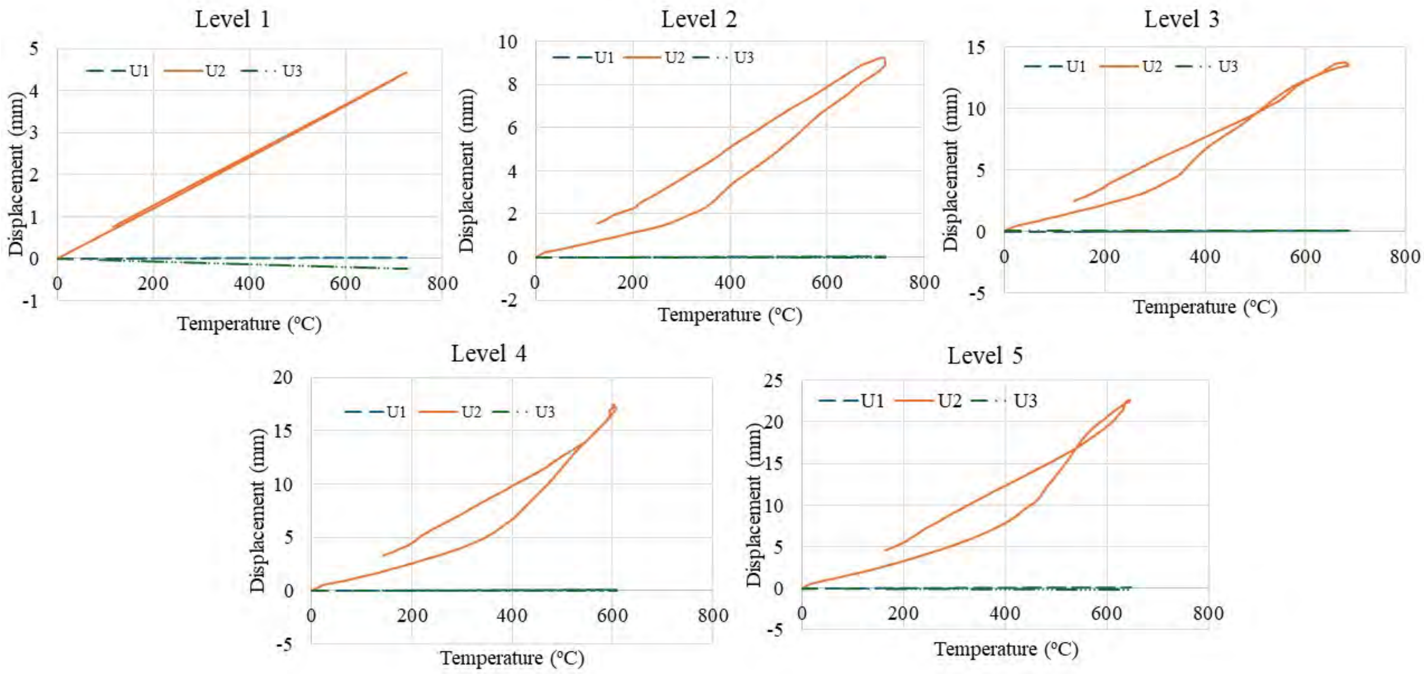

Figure 4. Deformation on the unloaded isolated column under thermal load at different heating zones

4.2 Eccentricity through position of axial loading

The deformation of the column under various eccentricity ratios is depicted in Figure 5. Figure 5(a) illustrates the buckling mode for the scenario of concentric axial loading, occurring along the axis of lower flexural rigidity. In cases of eccentric loading (Figure 5(b) and (c)), the deformation mode shifts to the weak axis (z-axis), where the load is applied at varying distances.

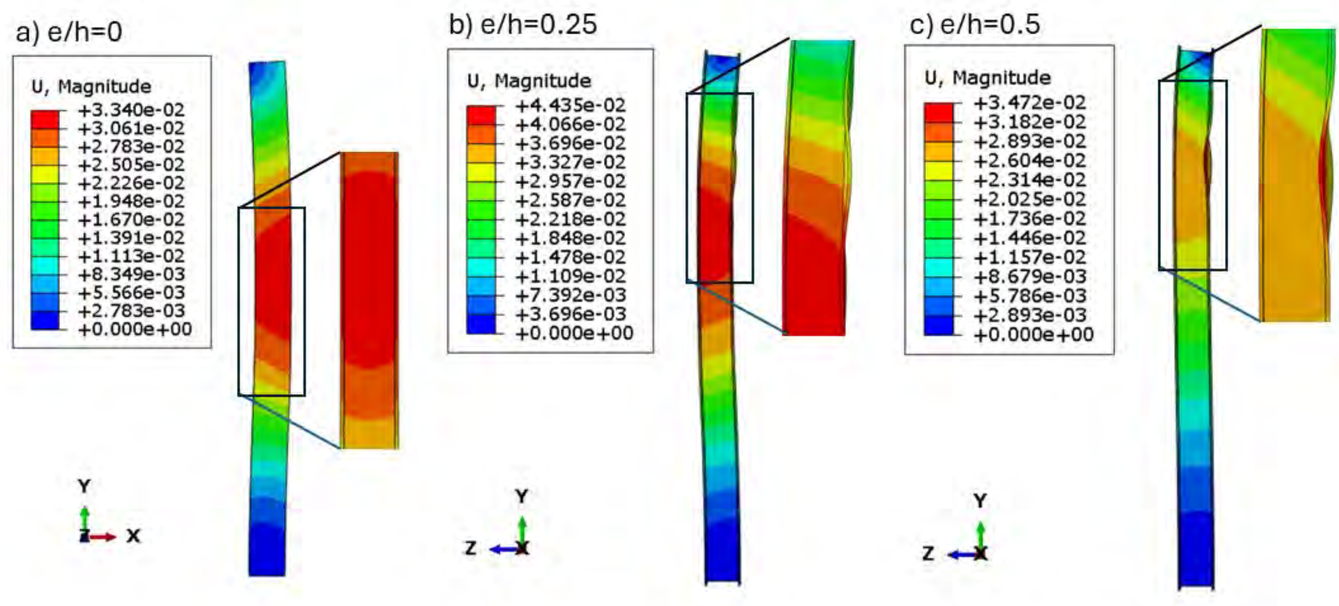

Figure 5. Column deformation at different eccentricities

Figures 6 and Figure 7 showcase the lateral displacement and axial deformation of the column when subjected to eccentric loading under a traveling fire scenario. As shown in Figure 6, that lateral deformation increased significantly with increasing temperatures, particularly at higher eccentricities. For the case when e/h=0, the lateral displacement remains constant regardless of temperature changes. A rapid increase in displacement occurs after reaching 500°C, resulting in an overall lateral displacement of 32 mm. For the case of e/h=0.25, a slight increase in lateral displacement is observed as the temperature rises. At 500°C, the lateral displacement reaches approximately 5 mm. Beyond 500°C, deflections increase exponentially, developing a final displacement of 42 mm. Notably, in both scenarios, the section fails to support the load at approximately the same time. Additionally, the start of local buckling in the flanges is observed due to eccentric loading, and the initiation of material yielding at the flanges is observed (refer to Figure 5(b)).

For the case of e/h=0.5 significant deformation begins immediately after the material is exposed to temperatures above 200°C, with lateral deformation increasing sharply beyond 400°C. The section begins to exhibit local buckling in the flanges and starts to fail before reaching 500°C. In the eccentric cases, it is observed that higher stresses develop in the section's flange, leading to failure in further load-carrying capacity of the section. Increasing the loading eccentricity significantly amplifies lateral deformation, with the most pronounced effect observed for e=b/4, indicating a higher susceptibility to deformation at elevated temperatures.

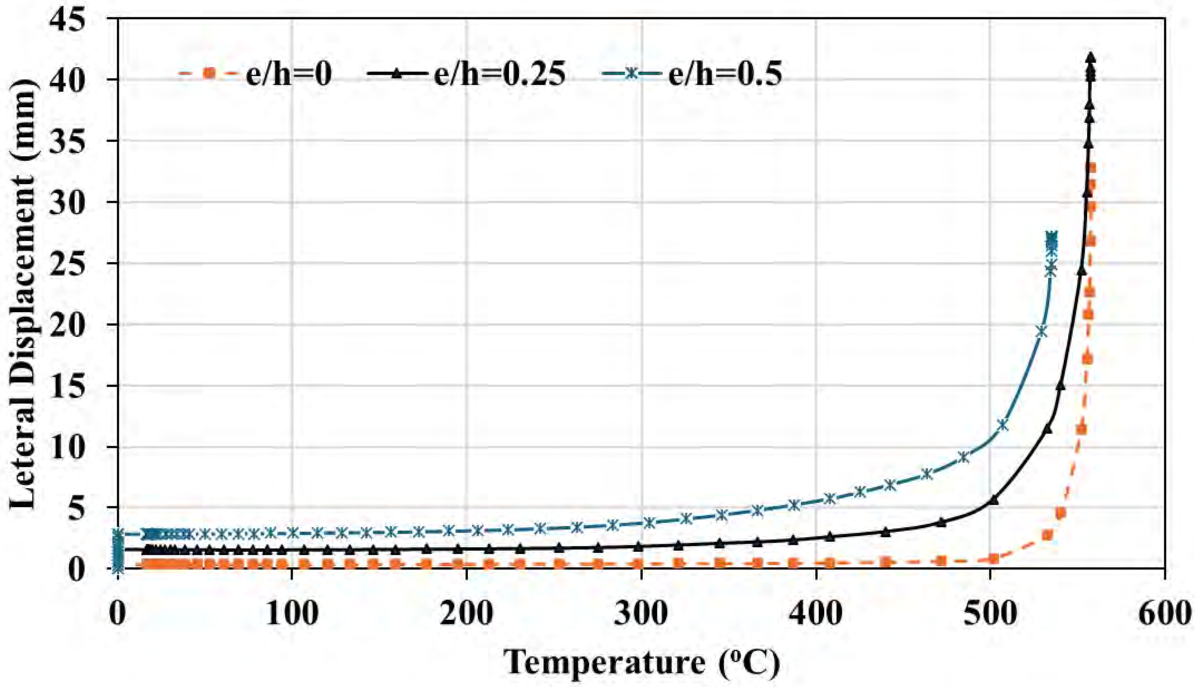

Figure 6. Lateral displacement in the isolated columns under different eccentricities

Figure 7 presents the results of axial deformation as a function of temperature for different eccentricity ratios. The temperature at which a column's axial deformation peaks is termed the buckling temperature; this temperature marks the onset of significant lateral deflection and buckling due to the column shortening under temperature [25]. As depicted in Figure 7, the buckling temperature for a column in the concentric case (e/h=0) is 530°C. For eccentricity ratios of e/h=0.25 and e/h=0.5, the buckling temperatures are 528°C and 504°C, respectively. Wang [26] defines the failure temperature of a restrained column as the point where the axial force in the column returns to its initial value. According to this definition, the failure temperatures for columns with eccentricity ratios of e/h=0, e/h=0.25, and e/h=0.5 are 568°C, 567°C, and 534°C, respectively. It is observed that increasing eccentricity reduces the buckling temperature, indicating that columns under eccentric loading fail earlier than those under concentric loading. Overall, the higher eccentricity ratio showed lower buckling temperature and the difference between failure temperature and buckling temperature was varied between 30°C to 40°C among considered eccentric ratio cases.

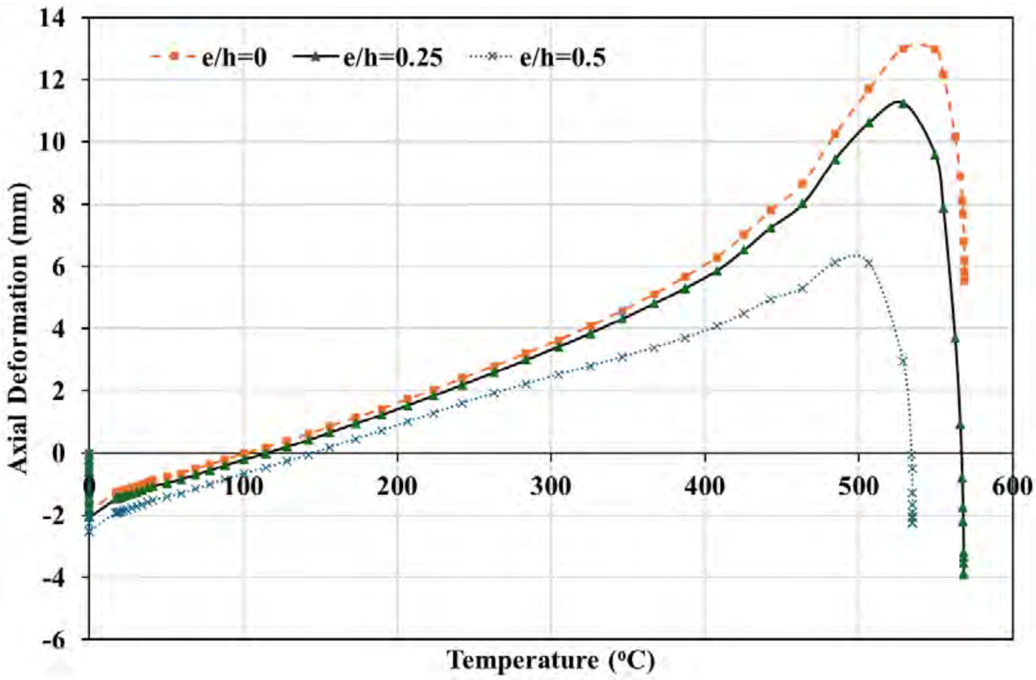

Figure 7. Axial deformation in the isolated columns under different eccentricities

4.3 Eccentricity through transient heating

4.3.1 Deformations in Column

Figure 8 illustrates the stress distribution in structural members under various eccentricity scenarios induced by transient heating. In Figure 8(a), the stress distribution in the members is depicted when the thermal load is exclusively applied to the column (Case 1, Table 1). Figure 8(b) showcases the stress levels when transient heating affects both the column and the beam along the left side (Case 2, Table 1). Figures 8(c) and 8(d) showcase the structural response at 20% and 30% of imposed loads combined with thermal load, respectively (Case 3 and Case 4, Table 1). Figure 9 depicts deformation in a frame frame under 30% imposed load in a travelling fire scenario. Deformation results for the column and beam are presented in Figure 10 and Figure 11, respectively. In Figure 10(a-d), the deformation under different scenarios outlined in Figure 8 is displayed. For Case 1, where the column is subjected to transient heating (Refer to Figure 10(a), the governing mode of deformation is along the axial direction, with minimal displacement (U1 and U3) along the orthogonal axes (x and z axes). The structure remains undamaged in this case, exhibiting no plastic deformation. Notably, the critical point where stresses are generated is at the beam-column connection. The final axial displacement (U2) in this case is recorded as 3mm . Conversely, in Case 2 where both the beam and columns are subjected to thermal load alone, as shown in Figure 10(b), vertical deformation (U2) occurs during the temperature rise, alongside deformation along the axes of lower flexural rigidity is developed in the z-direction (U3). This indicates combined axial and flexural deformations. Upon cooling, residual axial deformation in the column is observed as 3mm, similar to case 1, returning to its original position after temperature reduction.

For Case 3, where a 20% imposed load on the beam is applied along with the transient thermal load on the column and beam, the structures can sustain the load throughout the temperature duration, exhibiting elastic deformation. Additionally, deformation along the x-axis (U1) is observed alongside U2 and U3. After temperature reduction, final deformations occur primarily in the vertical direction and along the z-axis. In Case 4, with a 30% imposed load applied to the beam as shown in Figure 10(d), it becomes evident that the section starts to fail, resulting in deformation corresponding to the temperature rise. The maximum lateral displacement observed in a column is recorded as 10mm.

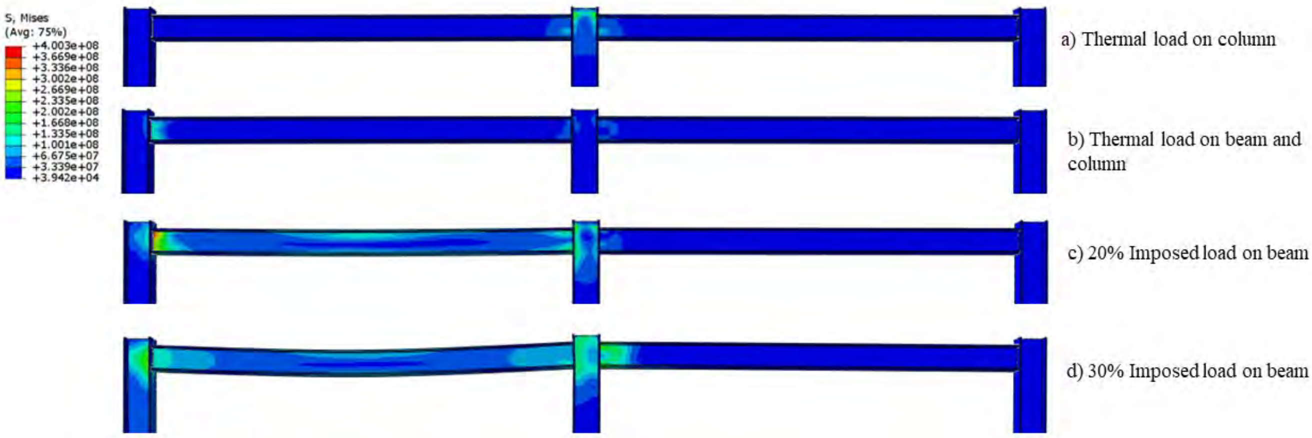

Figure 8. Stress distribution across members due to imposed load and thermal load

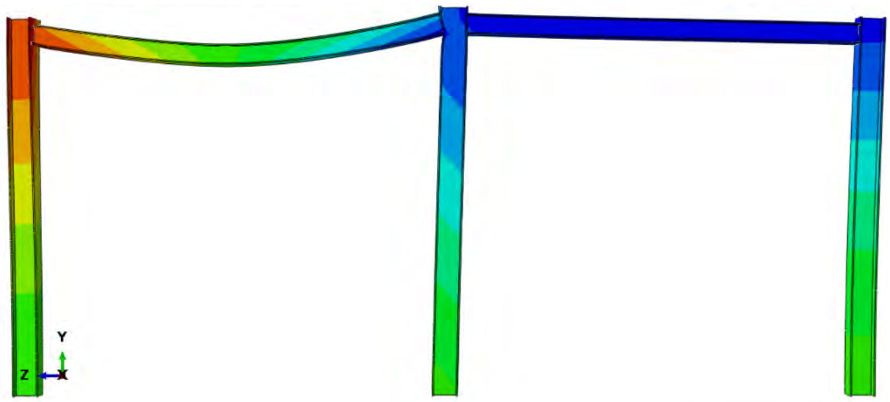

Figure 9. Deformation in a frame under 30% imposed load in a travelling fire scenario

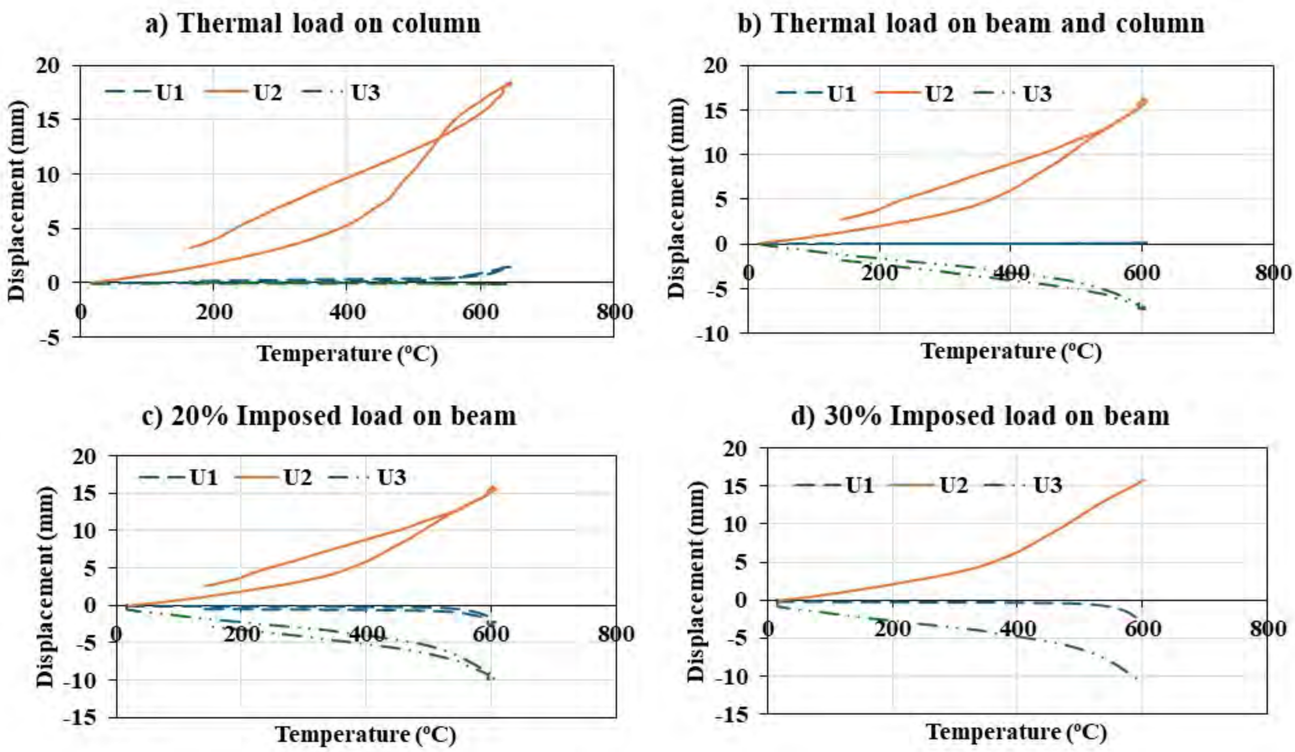

Figure 10. Deformation on a column in case of frame under thermal load with a combination of imposed load

4.3.2 Deformations in a beam

Furthermore, the response of deflection in the beam under imposed load in combination with transient thermal load is presented in Figure 11. For the unloaded case, in which only thermal load is applied, the section responds elastically by showing a deflection of merely 2 mm. It can be seen in Figure 8(a-d), that in all the loading cases the beam-column interactions are critical one which experiences higher stresses relative to other locations along the members. At 20% imposed load, the frame section can carry the load with temperature. Overall deflection produced in this case is 8mm. However, increasing the load by 30%, the sections start failing after 40 minutes of the thermal load. The maximum deflection recorded in this case is 10 mm. The adjacent column presented a slight twisting when a beam is subjected to transient heating and imposed load as shown in Figure 8. This could be attributed to the differential thermal environment of the beam and column, as the beam was subjected to temperature load, and the column was exposed to ambient conditions. It must be noted that the perfect connection between the beams and columns was modelled using the "Tie-Constraint" option available in ABAQUS.

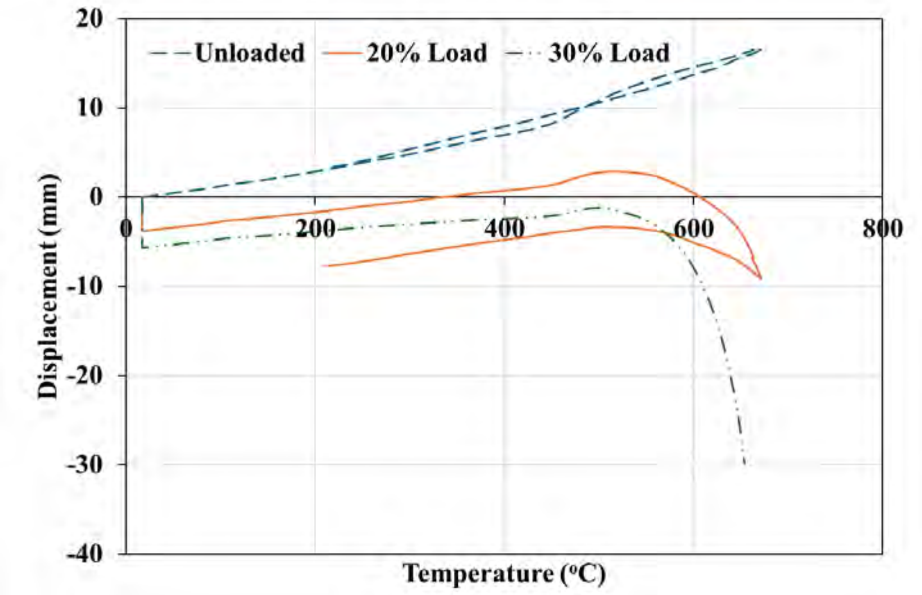

Figure 11. Beam Deformation under different loading

5 CONCLUSIONS

The study employed nonlinear analyses to explore the effects of eccentricities resulting from the applied loads and transient heating of columns during travelling fires. Abaqus software was utilized to simulate column buckling behaviour, accounting for geometric imperfections and material nonlinearity. The investigation focused on analysing stress distribution and deformation behaviour of structural members under transient heating scenarios with varying eccentricities. The key findings from the study are given below:

- Higher loading eccentricities intensify deformation, with local buckling observed in the flanges and initiation of material yielding. Temperature elevation, especially beyond 500°C, leads to substantial lateral displacement, ultimately resulting in section failure. Moreover, columns with higher eccentricity exhibited lower buckling temperatures. The variance between the failure temperature and the buckling temperature varied in the range of 30°C to 40°C.
- In case of steel frames, where transient heating affects both the column and frames, the structure remains intact without experiencing plastic deformation. It is noteworthy that the critical stress point occurs at the beam-column connection, with a residual axial displacement of 3mm.

- Transient heating with a 20% imposed load on the beam showed the structure withstands the load during the entire temperature duration, displaying elastic deformation. Upon cooling, the final deformations primarily apparent in the vertical direction and along the weak axis. However, when a 30% imposed load is applied to the beam, the section begins to fail, leading to deformations corresponding to the temperature rise. The maximum lateral displacement observed in a column is recorded at 10mm.
- Thermal loads induce additional forces and moments on the structure, leading to load redistribution within the beam-column interactions. This redistribution results in increased stresses at critical points within the beam column interaction.

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