THE DESIGN OF MOMENT CONNECTIONS FOR IMPROVED POST-FIRE SEISMIC PERFORMANCE

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Abstract

The criteria for selecting steel structures for post-fire reuse are simplified. A key consideration is the impact of elevated temperatures (fire) on the material properties and steel geometry. Another concern relates to poor understanding of the post-fire performance of steel under seismic loading, when cyclic loading, plastic-hinge formation and other similar effects are developed. The research explored the post-fire cyclic performance of unprotected beam-column connections. The steel connections are exposed to different fire scenarios based on standard and natural fire curves, resulting in modification of material properties and deformations. The deformations are limited to code defined limits for reinstatement. The post-fire performance under monotonic and cyclic loading was reviewed and compared with pre-fire performance using numerical simulations. The outcomes yielded useful insights about the design of moment connections for improved post-fire performance.

Keywords: Post-fire, Steel Structures, Moment Connections, Cyclic performance, Reinstatement

1 INTRODUCTION

The investigation of the seismic performance of steel structures has gained traction in the last decade through technology-driven numerical and experimental investigations of steel structures. The approach translated to the development of earthquake-resistant steel structures that exhibit limited structural and non-structural damage after seismic loading and potential application after earthquakes. The seismic performance has been augmented by extensive research on the performance of steel structures under fire attack, resulting in improved design methods for fire resistance of steel structures. However, post-fire reinstatement has not been widely studied, especially when the structure is built in earthquake-prone areas, resulting in exhaustive loading and plastic deformations. The safe post-fire reuse is important for the building owner/user (business continuation and repair cost.) as well as for estimating the insurance company compensations and premiums.

A majority of steel structures exposed to fire do not collapse and suffer limited structural damage; this increases the potential for reuse after exposure to fire. The One Meridian Plaza, Philadelphia, USA (1990) (USFA-TR-049, 1991), Churchill Plaza at Basingstoke (2005) (Wang, 2002), and Broadgate, London (1990) (P113, 1991) are cases in point. Following the Broadgate fire, investigations were undertaken, and it was confirmed that structural elements were not fireproofed and the active firefighting systems were not active during construction. Even though the fire lasted for nearly five hours under extreme temperatures (1000 ^{o}C), the performance of the steel structures was less impacted. Since the structural damage was minimal, the repairs were completed within a short period of time.

The reinstatement of steel structures after the fire event has key implications for post-fire deformations and the residual mechanical properties. According to previous studies, although the mechanical properties of steel are reduced at elevated temperatures, they can be recovered after cooling down to room temperature (Outinen *et al*., 2004; Lee *et al*., 2004; Tao *et al*., 2013; BS5950-8, 2003; Cooke, 1998; Li *et al*., 2003). The recovery level is a function of several parameters, including maximum temperature during heating, rate of cooling, the chemical composition of steel, thermal treatment of steel during production (Maraveas *et al*., 2017a). Upon cooling, the residual mechanical properties of high strength steel and bolts show higher degradation than ordinary steel due to thermal treatment of steel during production (Maraveas *et al.*, 2017a; Maraveas *et al.*, 2017b).

The reinstatement of steel structures is grounded on simplified criteria guided by literature (Tide, 1998; Kirby *et al.*, 1986; Smith *et al.*, 1986; Maraveas *et al.*, 2017a) and design codes (BS5950-8, 2003), which propose the reuse of steel structures after a fire. The proposal is only applicable in cases when the deformations are low. In addition, the specific limits of displacements and rotations are delineated. A fundamental question is whether the reuse of steel structures according to the simplified criteria is safe for accidental load combinations, like earthquake loading combinations.

The steel structures designed for high earthquake loads can survive a fire attack without considerable damage. Due to design against extreme seismic loads, the cross-sections are thick for better critical temperature and fire resistance. Furthermore, their load ratio is low. Based on the simplified criteria, these steel structures can be repaired and reused, even if the post-fire performance to earthquake loading has not been studied. The seismic performance is affected by the following parameters; mechanical properties of steel after exposure to elevated temperatures and cooling down, and post-fire residual deformations.

Critical structural elements for the performance of steel structures under seismic loading are moment beam-column connections, which are severally affected by post-fire degradation of mechanical properties of bolts (Maraveas *et al.*, 2017a; Maraveas *et al.*, 2017b; Maraveas *et al.*, 2021a; Maraveas et al., 2021b) investigated the seismic post-fire performance of a number of moment beam-column connection. The connections with the critical design component of the bolts (according to EN1998-1-8, 2005) were severely affected by fire in terms of moment resistance, stiffness and energy dissipation. This paper investigates proper methods for improved post-fire performance of such moment connections—especially the effect of over-design of connections on bolts' steel grade and diameter.

2 NUMERICAL SIMULATIONS’ METHODOLOGY AND VALIDATION

2.1 Simulation methodology and analysis parameters

In order to predict the post-fire cyclic performance of moment beam-column connections and the fire effect to cycle loading performance, the seven steps were chosen:

1. Development of the numerical connection model, including local imperfections (b/100 according to Maraveas et al., 2017c) and residual stresses (according to BSK 99 (Abambres et al., 2016).
2. Monotonic/cyclic loading of the connection following a specific applied displacement history for comparison reasons.
3. Perform coupled thermal – structural analysis. Three sides exposure of beam considered. During thermal analysis, a firing curve (standard fire curve or extreme parametric fires according to EN1991-1-2, 2015) is applied. The fire curve is cooling down when the post-fire displacements and rotations are near the limits per BS 5950-8, 2003. In order to approach the displacement or rotation limit, trial and correct rounds of analysis are repeated.
4. For the post-fire analysis, the maximum temperature developed in each node is set up as the initial temperature. The post-fire residual geometry from the coupled thermal-structural is used.
5. The post-fire residual mechanical model for structural steel and bolts is implemented according to Maraveas et al., 2017a.
6. The thermal expansion coefficient is given as zero.
7. Monotonic /Cyclic analysis is performed for the post-fire connection is performed and compared with the pre-fire performance of the connection. The used methodology is shown as a flowchart in Figure 1.

2.2 Validation against experimental results

The validation of numerical models against experimental results from the literature. The validation against experimental results presented by ElSabbagh et al., 2019 were specific to simulation connections under cyclic loading. The validation against experimental results presented by Santiago, 2008 and Santiago et al., 2010 focused on thermal and structural analysis of connections under fire. Detailed information is presented in Maraveas et al., 2021b.

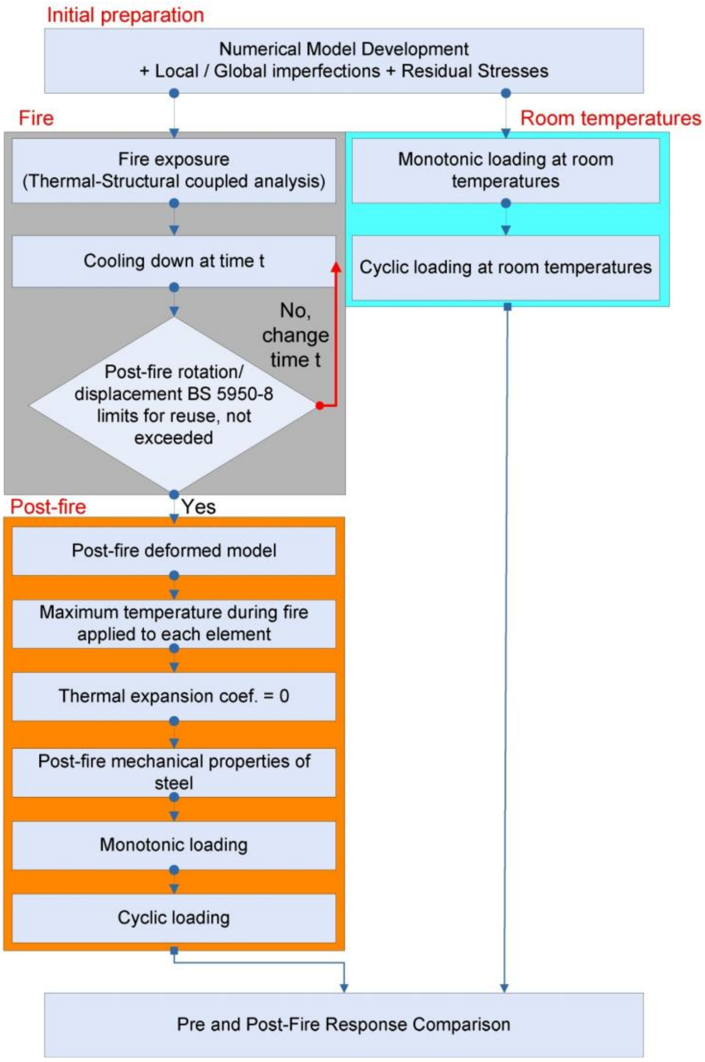


Fig. 1 Flowchart of applied methodology (Maraveas et al., 2021b)

2.3 Geometry of studied connection and proposed modifications

The studied connection is presented in Fig. 2. Two modifications examined in order to assess their post-fire performance. First, the bolts steel grade modified to 10.9 and second, the diameter of bolts changed to M22.

3 SIMULATION RESULTS

3.1 Temperatures during fire exposure

The developed temperatures on steel members and bolts are shown in Fig. 3. For standard fire exposure, the temperatures of bolts exceed 500 ^{o}C while steel approached 700 ^{o}C. For fast fire exposure, the maximum temperatures were similar. For slow fire exposure, the developed temperatures were lower than standard and their effect on the post-fire performance of the connections limited.

3.2 Post-fire monotonic performance

The analysis of the examined steel connection for (a) increased bolt grade and (b) increased bolt diameter is shown in Fig. 4. From these graphs, it can be seen that when the steel grade is increased, the post-fire moment capacity increased too, but stiffness does not considerable change. Similarly, when the bolt diameter increased, similar performance obtained.

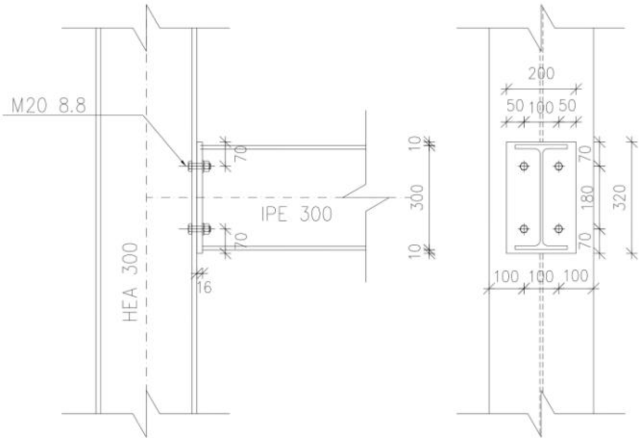


Fig. 2 Studied connection (Maraveas et al., 2021b)

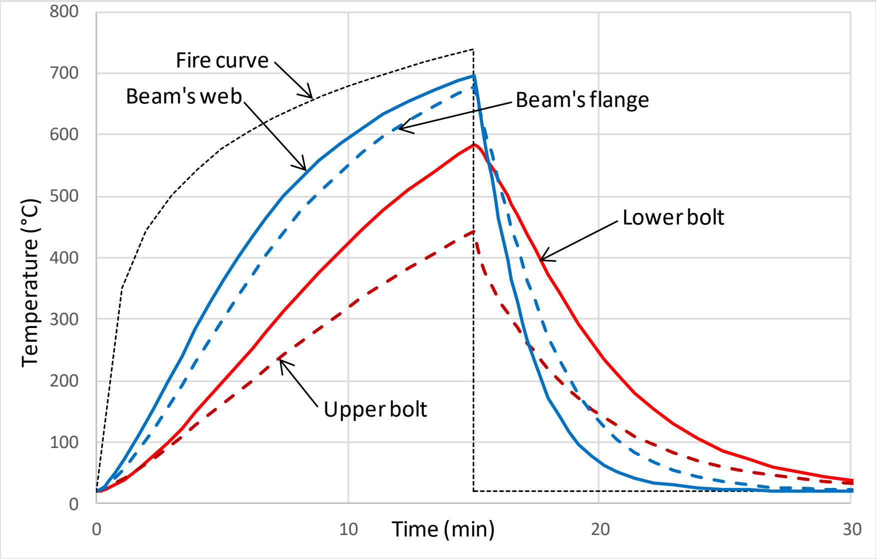


Fig. 3 Temperatures on steel and bolts for Standard fire exposure (Maraveas et al., 2021b)

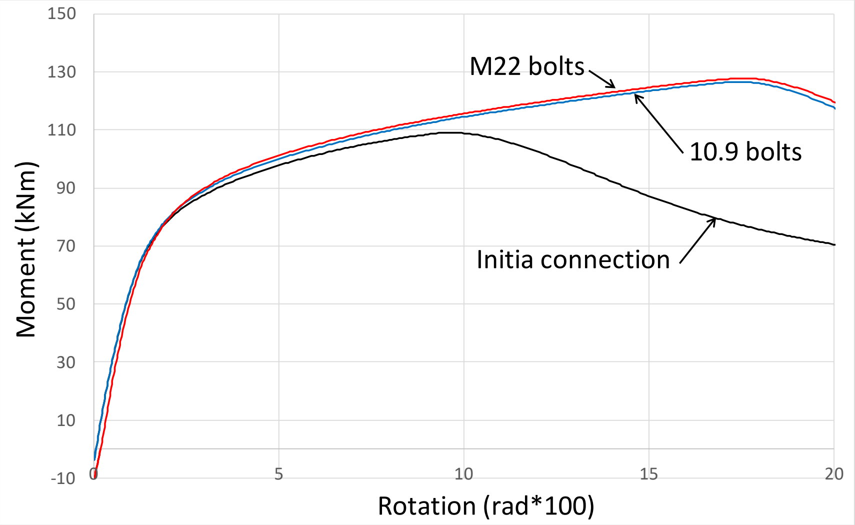
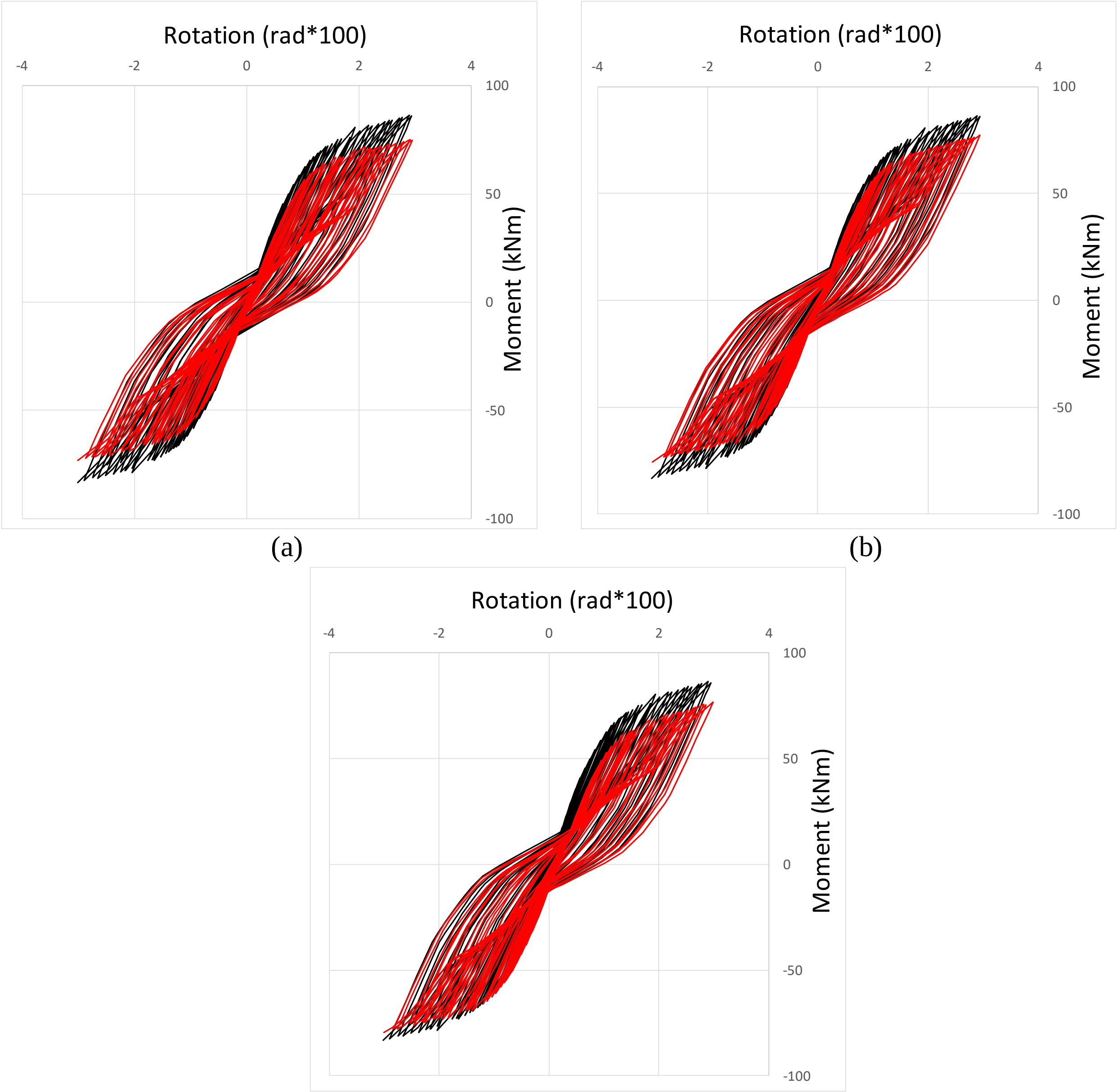


Fig. 4 Post-fire moment-rotation monotonic diagrams of connection as in Fig. 2 compared with same connection with steel bolts' grade 10.9 and with bolts' diameter M22

3.3 Post-fire cyclic performance

The post-fire cyclic loaded performance of the studied connections with proposed modifications are presented in Fig. 5. The performance for increased bolt diameter does not have any change, but the performance for increased bolt grade is improved in terms of energy dissipation.



(a)

(b)

(c)

Fig. 5 Post-fire moment-rotation cyclic diagrams of connection (a) as in Fig. 2, (b) with bolts' grade 10.9 and (c) with bolts' diameter M22 vs the pre-fire response of the connection (black lines) of Fig. 2

4 CONCLUSIONS

This paper presents initial research on possible design improvements of steel moment connections for post-fire reinstatement without replacing the bolts. Extensive numerical simulations performed with the use of the novel methodology. The over-design of bolts to reduce the fire effects on the connection and achieve improved moment capacity, stiffness and energy dissipation during an earthquake was noted. The bolts changed to 10.9 - a grade higher than the initial design- and the post-fire moment capacity was increased, but in terms of stiffness, there was limited improvement. The increase in bolts' diameter from M20 to M22, improved the post-fire moment capacity but the stiffness improvement and energy dissipation under cyclic loading was limited. Given the limitations of this research (only one connection was analysed), there is a need for further investigations.

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