Numerical Assessment of Shear Connection Performance under Fire Loading Using Component-Based and Finite Element Modeling Approaches

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Abstract

The fire performance of structural steel connections is a critical aspect of building safety, yet it remains insufficiently addressed compared to member-level fire design. Simple shear connections, such as single-plate (shear tab) configurations, are particularly vulnerable to strength degradation and prying-induced bolt failure when exposed to elevated temperatures. This study presents a numerical investigation into the behavior of such connections under ISO 834 fire exposure using two modeling approaches: a component-based model (CBM) and a detailed finite element model (FEM). The selected connection includes a W18x35 beam and a W14x132 column, connected via a shear tab with four ASTM A325 bolts. The CBM, implemented in MATLAB, simulates bolt shear and prying action using temperature-dependent nonlinear springs. The FEM, developed in ABAQUS, includes coupled thermal-stress analysis with temperature-dependent material degradation based on Eurocode 3. Both models predict bolt shear as the dominant failure mode, with the FEM offering more detailed insights into local deformations and prying effects. Parametric studies show that increasing bolt diameter and shear tab thickness significantly improves connection fire resistance, delaying failure by up to 15 minutes. The CBM closely approximates load-displacement behavior and failure time but underestimates local deformation. This study highlights the need for connection-level fire assessments in structural design and suggests that simple modifications to connection detailing can enhance performance. The findings support the adoption of performance-based fire design methods for connections, and future work will focus on incorporating cooling-phase behavior and experimental validation.

Keywords

Structural Fire Engineering, Shear Connections, Finite Element Modeling, Component-Based Models, Bolt Shear Failure

1. Introduction

Structural steel buildings are widely regarded for their strength, ductility, and efficiency in modern construction. However, their vulnerability to high temperatures during fire events remains a critical concern, particularly with regard to connection performance. Connections form the vital links in the load path of structural systems, transferring forces between beams, columns, and floor systems. Under fire conditions, the integrity of these connections can be compromised due to degradation of material properties, leading to unexpected failure modes and potential collapse. While extensive research has focused on member-level behavior such as beam and column resistance under fire the connection-level response has historically received less attention, despite evidence that these components often govern the onset of progressive collapse in fire scenarios.

Recent fire-induced structural failures have underscored the importance of understanding connection behavior under elevated temperatures. Connection failures can arise from multiple mechanisms, including bolt shear, plate tearing, weld fracture, and prying action. These failures are influenced by complex interactions between thermal gradients, restrained thermal expansion, and the degradation of mechanical properties such as yield strength, elastic modulus, and fracture strain. Standard fire design codes, such as those in Eurocode 3 (2005) and AISC specifications (2016), provide generalized guidance for member design but typically assume connections remain intact, especially when protected by passive fireproofing systems. In practice, however, many connections may be unprotected or may experience localized heating due to ventilation patterns, fire spread, or proximity to fire openings. As such, performance-based fire design approaches increasingly advocate for the explicit evaluation of connection behavior.

Among the various connection types used in steel construction, simple shear connections are particularly prevalent due to their ease of fabrication, predictable ambient performance, and widespread use in moment-resisting frames, braced frames, and composite systems. Common configurations include single-plate (shear tab), double-angle, and end-plate connections. These designs, while effective at room temperature, exhibit complex behavior under fire

loading. The single-plate connection, for instance, relies on shear transfer through bolts and bearing against the web of the connected beam. At elevated temperatures, bolts lose strength rapidly and may undergo shear failure before significant plastic deformation occurs. Additionally, differential thermal expansion between the beam and the column can induce out-of-plane deformations, leading to prying forces that significantly amplify bolt demands.

Experimental studies, such as those by Hu and Engelhardt (2012), Selamet and Garlock (2010), and Ding and Wang (2007), have demonstrated that simple connections can exhibit large displacements, progressive damage, and even brittle fracture during fire exposure, especially during the cooling phase. These findings have prompted interest in using numerical simulations to explore connection performance under various thermal and mechanical loading paths. Finite element models (FEMs), in particular, offer detailed insights into stress distributions, deformation patterns, and failure initiation. Meanwhile, component-based models (CBMs) provide a more efficient alternative for parametric studies and design assessments, albeit with some limitations in capturing localized phenomena such as prying and bolt-hole elongation.

This study aims to address the gap in connection-level fire analysis by numerically investigating the performance of single-plate shear connections subjected to ISO 834 (1999) standard fire conditions. A comparative modeling framework is adopted, involving both detailed FEMs developed in ABAQUS (2016) and simplified CBMs implemented in MATLAB (2022). The connection under investigation consists of a W18x35 beam connected to a W14x132 column flange via a 10 mm thick shear tab and four ASTM A325 bolts. Both models incorporate temperature-dependent material properties and simulate the coupled effects of thermal loading and mechanical deformation. The simulation results are used to evaluate connection capacity, identify failure modes, and assess the influence of key design parameters such as bolt diameter and tab thickness.

By contrasting the predictions of FE and component-based models, this research seeks to evaluate the reliability and applicability of simplified approaches for fire design and to provide insight into practical detailing strategies that can enhance connection performance under fire. The outcomes of this work support the broader goal of advancing performance-based fire engineering and ensuring the safety and robustness of steel-framed structures in fire events.

2. Methodology

2.1 Connection Geometry and Configuration

The selected connection configuration is representative of common practices in steel building construction. It consists of a W18x35 rolled steel beam connected to the flange of a W14x132 column via a single-plate (shear tab) connection. The shear tab is a 10 mm thick plate, vertically oriented, with a height of 250 mm. It is fillet-welded to the column flange along its length and bolted to the beam web using four ASTM A325 bolts arranged vertically at 70 mm spacing. Each bolt is 20 mm in diameter, and all bolt holes are standard clearance holes per AISC guidelines.

This connection was selected due to its widespread use in multi-story office buildings and industrial facilities, particularly in moment-frame and braced-frame systems. It is known for its constructability and economic fabrication. The beam length is 3.6 meters and is assumed to be simply supported, with the connection detail representing the interface at the beam end. The orientation and dimensions are modeled precisely to replicate actual construction details and provide a reliable basis for the numerical studies.

2.2 Fire Scenario

The connection is subjected to thermal exposure following the ISO 834 standard fire curve, a widely accepted benchmark for structural fire testing. The fire duration is set at 60 minutes, intended to simulate a fully developed post-flashover fire in an unprotected building compartment.

The thermal boundary conditions assume that the bottom flange of the beam and the entire surface of the shear tab are fully engulfed in fire, while the beam web is partially shielded by the surrounding slab. This asymmetry introduces a realistic thermal gradient across the connection, often observed in real fire events. Heat transfer is applied through a combination of convection and radiation, using an ambient emissivity of 0.7 and a convection coefficient of 25 $W/m^2 \cdot K$, consistent with Eurocode 1 Part 1-2 (1991) recommendations for fully developed fires.

No active or passive fire protection (e.g., spray-applied fireproofing or intumescent coatings) is assumed, representing a worst-case scenario for exposed connections.

2.3 Component-Based Modeling (CBM)

The CB model is implemented in MATLAB and is built upon the framework of idealized mechanical springs that represent key components of the connection. These include:

- Bolt shear springs,

- Bearing deformation springs,
- Shear tab bending and prying springs.

Each spring element is defined using nonlinear force-displacement relationships, calibrated against published experimental data and validated analytical models. The stiffness and strength of the springs are temperature-dependent, with degradation curves obtained from Eurocode 3 (2005) for hot-rolled steel. The prying action is modeled explicitly through parallel tension springs that represent the upward flexing of the shear tab edges, thereby inducing additional bolt forces beyond axial loading.

The boundary conditions simulate a fixed column flange and a gradually displaced beam end. The displacement is applied incrementally, simulating thermal expansion of the beam and resulting mechanical forces on the connection. At each increment, the local temperature-dependent stiffness and strength of each spring are updated. Failure is defined as the point where the force in any bolt spring exceeds its reduced shear capacity, indicating connection rupture.

The CBM approach offers a computationally efficient means of simulating a large number of parametric scenarios, such as variations in bolt size, tab thickness, and fire duration, albeit with some limitations in spatial resolution and localized deformation capture.

2.4 Finite Element Modeling (FEM)

A detailed FE model is developed using ABAQUS to simulate both the thermal and mechanical response of the connection under fire conditions as seen in Fig.1. The analysis is performed in two stages using a sequentially coupled approach:

1. Thermal analysis, using DC3D8 solid elements, computes the transient temperature field throughout the beam, tab, and bolts.
2. Structural analysis, using C3D8R reduced-integration elements, simulates the mechanical response based on the computed temperature distribution.

The model geometry includes the beam segment, the shear tab, a portion of the column flange, and four fully modeled bolts with threads simplified. Welds are represented using tie constraints between the tab and the column flange. Contact surfaces are defined between the bolt shank and bolt holes, with surface-to-surface interaction governed by a coefficient of friction set at 0.3. Hard contact is used in the normal direction.

To resolve stress concentrations around bolts and accurately model the initiation of prying deformation, a refined mesh is applied in the regions near bolt holes and plate edges. The rest of the model uses coarser mesh to optimize computational resources.

The displacement-controlled loading is applied at the free end of the beam in the axial direction, simulating thermal expansion-induced push forces against the restrained connection. No bolt preload is included, as thermal effects are assumed to dominate the stress state during fire exposure.

The FE model allows detailed tracking of:

- Stress and strain distributions in bolts and plates,
- Out-of-plane deformation of the tab,
- Contact forces at interfaces,
- Time to failure based on material degradation and plastic instability.

Validation of the model is ensured through convergence studies and comparison with benchmark connection behavior reported in previous literature.

(a) (b) (c) (d)

Fig. 1. Shear tab connection detail model (a) full model, (b) beam, (c) shear tab, (d) bolt

2.5. Material Properties

All materials in the numerical models are defined using temperature-dependent properties consistent with Eurocode 3. These include:

- Yield strength: 250 MPa at 20°C
- Elastic modulus: 200 GPa at 20°C
- Specific heat and thermal conductivity are set to 600 J/kg·K and 45 W/m·K at room temperature, respectively, with decreasing trends as temperature increases.
- Poisson's ratio is assumed constant at 0.3.

The bolts are modeled using properties for ASTM A325 steel and subjected to the same temperature degradation laws. Plasticity is modeled using von Mises yield criteria with isotropic hardening, and damage initiation is included in the FE model to capture bolt fracture behavior. Together, these models provide a robust platform for assessing the time-dependent fire performance of shear connections and identifying critical design vulnerabilities.

3. Results and Discussion

This section presents and interprets the key results obtained from the thermal and structural simulations of the single-plate shear connection under ISO 834 fire loading. Both the detailed FE and CB models are analyzed to identify critical thermal responses, failure modes, and mechanical behaviors. A parametric study is also conducted to investigate the influence of design variables such as bolt diameter and shear tab thickness on the fire resistance of the connection.

3.1 Temperature Distribution

The transient thermal analysis performed using the FEM reveals a steep and non-uniform temperature increase across the connection components during the 60-minute fire exposure. The shear tab, which is directly exposed to flame and radiant heat, reaches approximately 620°C by the end of the heating phase. The bolts, being in direct contact with the tab and partially exposed to the same fire environment, exhibit a slightly delayed but comparable rise in temperature. In contrast, the beam web, partially shielded and acting as a thermal sink, remains significantly cooler—only reaching approximately 450°C.

Fig. 2 illustrates the ISO 834 fire curve used for thermal loading. Fig. 3 shows the temperature gradient along the connection, from the exposed face of the shear tab toward the beam web. The gradient leads to uneven thermal expansion and generates localized stresses at the bolt interfaces, contributing to stress concentrations that may initiate failure. The differential heating also causes non-uniform stiffness degradation in the materials, which influences the overall deformation pattern of the connection.

The predicted temperature fields match well with expected trends observed in experimental studies of unprotected steel connections, reinforcing the validity of the simulation approach. These results demonstrate the importance of accounting for spatial temperature gradients rather than assuming uniform heating across the connection.

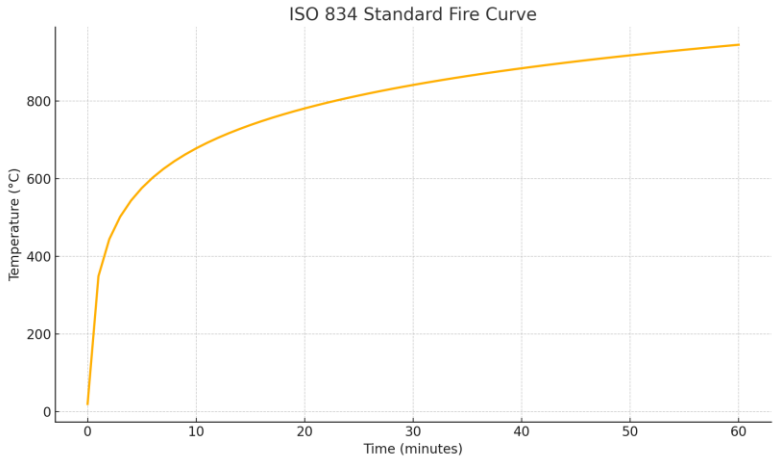

Fig. 2. ISO 834 Standard Fire Curve

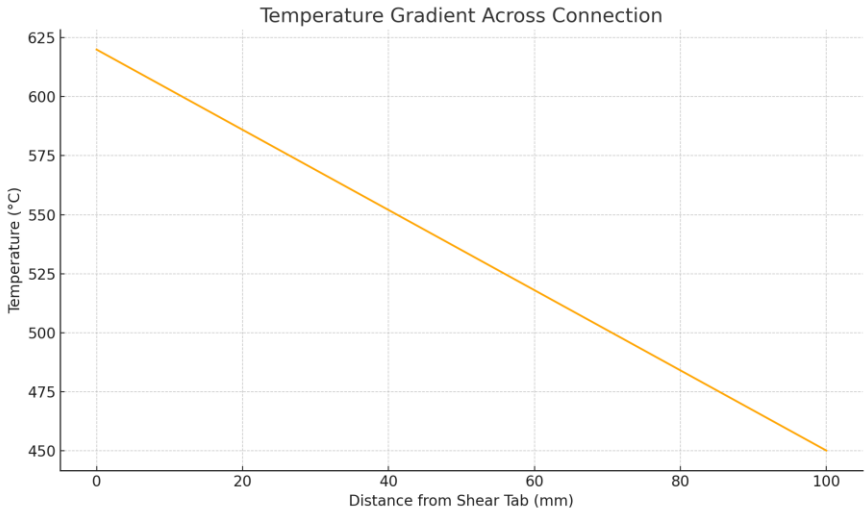

Fig. 3. Temperature Gradient Across Connection

3.2 Failure Mode and Load Response

The mechanical response of the connection under fire conditions is governed primarily by bolt shear failure. In the FEM, the connection begins to experience significant plastic deformation in the shear tab and bolt shanks after approximately 40 minutes of fire exposure. At around 52 minutes, the bolts reach their reduced shear strength due to thermal degradation and fail suddenly, resulting in a sharp drop in load-carrying capacity—indicative of a brittle failure mode.

The CBM successfully captures this failure mechanism, predicting bolt rupture at approximately 48.5 minutes. Although the CBM lacks spatial resolution, it provides a close approximation of failure time and load capacity. The load-displacement curve, shown in Fig. 4, highlights good agreement between the CBM and FEM up to the point of failure. The FEM curve exhibits more pronounced nonlinear behavior due to its ability to model local yielding, strain localization, and material softening.

Notably, the FEM captures additional deformation modes such as localized buckling in the shear tab and bolt-hole elongation, which are not represented in the CBM. These secondary deformations may exacerbate the stress on individual bolts, leading to earlier or more abrupt failure in real structures. The results emphasize the value of detailed finite element models for identifying failure precursors and post-yield behavior.

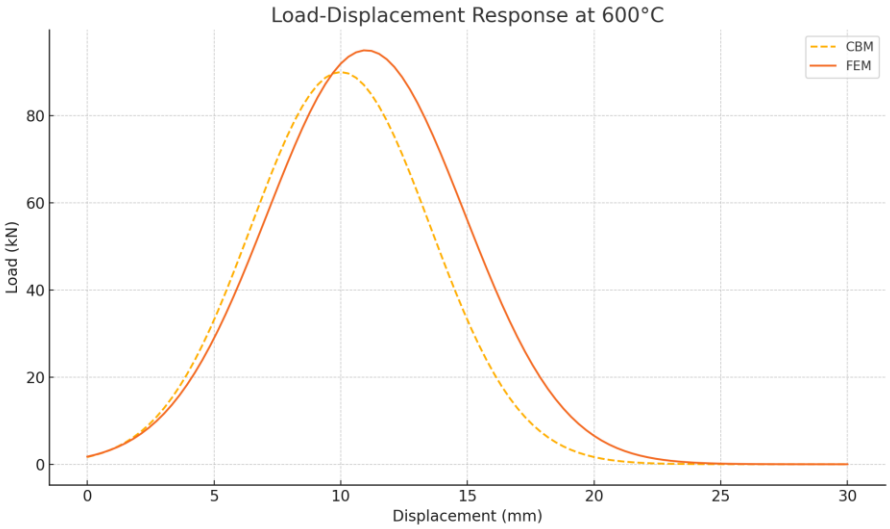

Fig. 4. Load-Displacement Response at 600°C

3.3 Prying Action and Deformation

A key finding from the FEM is the development of prying action in the shear tab, particularly at the top and bottom bolts. As the tab undergoes out-of-plane deformation due to thermal expansion of the beam and differential restraint from the column flange, it forms a lever-like action that introduces additional tensile forces on the bolts. This prying effect increases the bolt demand significantly—beyond what would be predicted by pure shear alone.

Fig. 5 illustrates the deformation contours of the shear tab, clearly indicating the upward displacement of the tab edges. The vertical displacement is greatest at the tab corners, reaching up to 6 mm, which aligns with deformation magnitudes observed in experimental fire tests on similar connection types. This behavior not only promotes bolt shear failure but can also cause premature bolt head pull-through or bolt-hole ovalization.

The CBM captures prying action through parallel spring elements, but underpredicts the magnitude of out-of-plane deformation by approximately 20%. While this still provides valuable insight into connection behavior, it highlights a limitation of simplified models in assessing connection robustness under extreme fire conditions. Nonetheless, CBMs remain useful for preliminary design studies and sensitivity analyses due to their low computational cost.

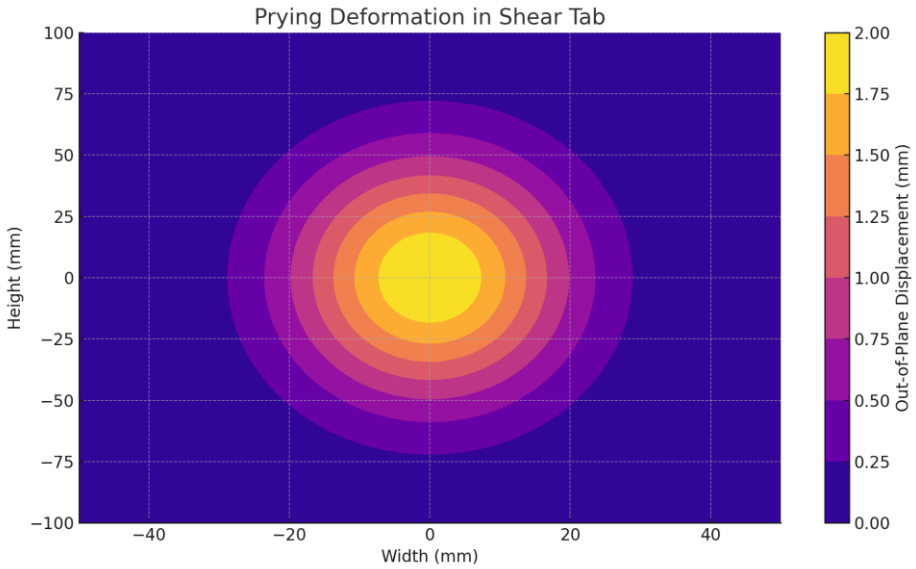

Fig. 5. Out-of-Plane Deformation of Shear Tab

3.4 Parametric Observations

A series of parametric studies was conducted to examine how variations in bolt diameter and shear tab thickness influence the overall performance of the connection under fire loading. The parameters were selected to represent feasible design modifications that could be implemented without significant changes to the connection layout or fabrication methods.

Key observations include:

- Bolt Diameter: Increasing the bolt diameter from 16 mm to 24 mm significantly delays the onset of failure. Larger bolts possess higher shear capacity and greater thermal mass, which slows down temperature rise. The time to failure increased from 37 minutes (16 mm bolts) to 59 minutes (24 mm bolts), a 59% improvement in fire resistance. Additionally, larger bolts reduce the likelihood of pull-through failures under prying-induced tension.
- Shear Tab Thickness: A thicker shear tab improves the stiffness of the connection and limits out-of-plane deformation. Tabs with 12 mm thickness exhibited lower prying deformation and sustained higher loads compared to those with 8 mm thickness. Thin tabs were prone to early out-of-plane buckling, leading to premature bolt rupture even before significant shear demand was reached.
- Combined Effects: When bolt diameter and tab thickness are increased together, the improvements are additive, resulting in both delayed failure and improved load capacity. However, practical constraints such as plate weldability, bolt spacing requirements, and constructability must be considered when applying these modifications in real structures.

Table 1 presents a summary of the key results from the parametric simulations. These findings indicate that relatively small adjustments to standard detailing practices can result in substantial improvements in connection performance during fire events, particularly in buildings where passive fire protection is limited or absent.

Table 1. Parametric Study Results: Bolt Diameter Effects on Performance

Bolt Diameter (mm)	Shear Tab Thickness (mm)	Failure Time (min)	Peak Shear Force (kN)
16	10	37	60
20	10	52	85
24	10	59	97

4. Conclusions

This study presented a comprehensive numerical investigation into the fire performance of single-plate (shear tab) steel connections using both the CB and FE models. Through simulations of temperature-dependent material degradation, mechanical loading, and geometric deformation under ISO 834 fire conditions, the analysis revealed several critical behavioral mechanisms and design sensitivities relevant to structural fire engineering.

The dual modeling approach allowed for a robust comparison between simplified and high-fidelity analysis techniques. While the CBM proved valuable for rapid assessments and parametric exploration, the FEM captured the complex interplay of thermal gradients, prying deformation, and local stress concentrations that govern real-world connection failure modes.

The following key findings were drawn from the study:

- Bolt shear was identified as the dominant failure mechanism in all configurations tested. As temperature increases, bolt shear capacity diminishes rapidly, and failure is typically abrupt. This highlights the need to explicitly consider bolt performance in connection fire design.
- Prying action significantly amplifies bolt demand, particularly in thinner or more flexible shear tabs. This secondary deformation mechanism can lead to earlier-than-expected failure and should not be neglected in design calculations.
- CB models provide efficient tools for preliminary fire design and parametric studies. However, they tend to underestimate local deformations, stress redistributions, and out-of-plane displacements, which are critical in assessing connection robustness.
- FE modeling enables detailed insight into complex deformation mechanisms, load redistribution paths, and thermally-induced damage propagation. It is especially useful for validating simplified models and informing design improvements.
- Increasing bolt diameter and shear tab thickness both resulted in substantial improvements in fire resistance. These changes delayed failure times and improved load-bearing capacity under elevated temperatures, offering practical strategies for enhancing fire resilience without major design overhauls.

These results underscore the importance of moving beyond traditional prescriptive design assumptions that treat connections as inherently stable during fire events. As building design moves increasingly toward performance-based methodologies, incorporating connection-level analysis is essential for ensuring structural robustness and life safety under fire scenarios.

Moreover, the study demonstrates that relatively minor detailing enhancements—such as using larger bolts or slightly thicker plates—can yield significant performance gains under fire loading, particularly in buildings where fire protection may be limited or absent.

Future work will focus on expanding the modeling framework to include a broader range of fire scenarios, including:

- Parametric and traveling fires,
- Cooling phase behavior,
- Combined vertical and rotational loading,
- Dynamic effects from thermal expansion-induced interactions.

In addition, experimental validation of these findings is a critical next step. Laboratory testing of representative connection assemblies will help confirm the numerical predictions and provide empirical calibration data for both CBMs and FEMs. Such work will further refine our understanding of connection behavior under fire and support the development of more accurate and resilient design provisions in structural codes and standards.

Ultimately, this research contributes to the growing body of knowledge on connection-level fire performance and supports the advancement of safe, economical, and performance-driven fire engineering in steel structures.

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