Proceedings of the
Annual Stability Conference
Structural Stability Research Council
Atlanta, Georgia, April 21-24, 2026

Numerical investigation of localized failure at plate thickness transitions in steel bridge girders exposed to fire

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Abstract

Steel plate girders in highway bridges are commonly optimized by varying bottom flange thickness along the span to efficiently resist nonuniform bending demands. While this practice improves material efficiency, the resulting thickness transitions introduce geometric discontinuities that alter local stiffness and stress flow. Under ambient conditions, such details are primarily addressed through detailing provisions based on fatigue failure. However, their behavior under fire exposure, where material degradation, thermal gradients, and instability effects dominate, remains poorly understood. This paper presents a numerical investigation of localized failure mechanisms at bottom flange plate thickness transitions in steel bridge girders subjected to fire. Advanced coupled thermo-mechanical finite element models are developed to capture non-uniform fire exposure, temperature-dependent degradation of steel properties, geometric nonlinearity, and composite action with the concrete deck. A representative composite steel plate girder with a variable bottom flange is analyzed under standard and hydrocarbon fire scenarios, with particular emphasis on stress redistribution, plastic strain localization, and instability initiation in the transition region. Results demonstrate that flange thickness transitions act as stability-critical details under fire exposure. Across all scenarios examined, localized instability consistently initiates at the thickness transition prior to global strength loss or attainment of deflection-based performance limits. The abrupt stiffness mismatch between adjacent flange segments promotes concentrated plastic strain accumulation in the thinner flange, further amplified by non-uniform temperature fields and differential thermal expansion. The findings indicate that conventional fire resistance assessment approaches based on uniform temperature assumptions, sectional capacity, or global response metrics may not adequately capture localized failure mechanisms in girders with geometric discontinuities. Overall, this study provides new insight into an overlooked localized stability problem and highlights the need to explicitly consider geometric discontinuities in performance-based fire assessment of steel bridge girders.

Keywords: Steel bridge girders; Thickness transition; Fire-damage; Finite element analysis.

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1. Introduction

Steel plate girders used in highway bridges are commonly optimized by varying flange plate thickness along the span to efficiently resist spatially varying bending demands. Thicker flange plates are typically provided in regions of high positive moment, while thinner plates are used where demands are lower, as schematically illustrated in Figure 1. Although this practice improves material efficiency, it introduces geometric discontinuities at plate thickness transitions that alter local stiffness and stress flow and can create stress concentrations (Taras and Unterweger, 2013).

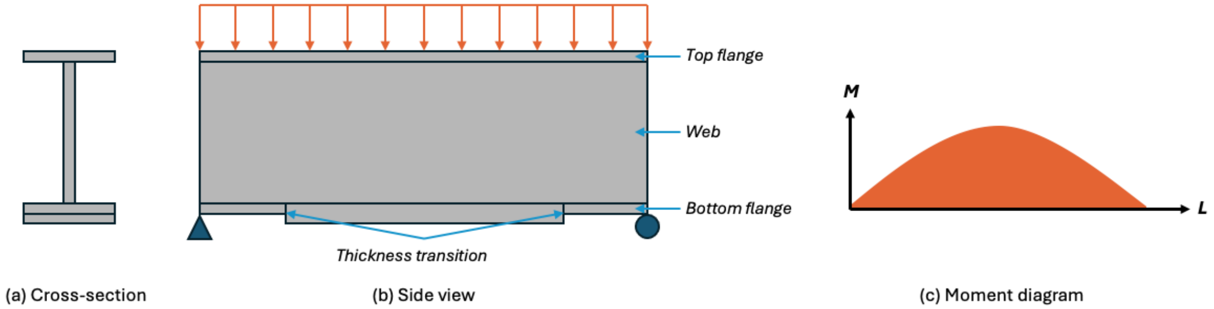

Figure 1: Bottom flange transition thickness in a steel bridge girder

Under ambient conditions, the structural implications of such transitions are typically addressed through detailing provisions intended to limit stress concentration and secondary bending effects. Current bridge design specifications and fabrication guidelines, including the AASHTO LRFD Bridge Design Specifications (AASHTO, 2024) and AISC 360 (AISC, 2022), recommend the use of gradual thickness tapers, minimum transition lengths, and smooth geometric profiles to promote more uniform force transfer between adjacent flange segments. In welded transitions, additional detailing practices, such as appropriate weld sizing, controlled weld terminations, and alignment tolerances, are commonly employed to mitigate crack initiation (Derler et al., 2023).

From a design perspective, the influence of stress concentration at thickness transitions is most explicitly considered in fatigue and fracture evaluations, where such details are classified into fatigue categories and assessed using nominal-stress or hot-spot stress approaches (Derler et al., 2023; Röscher et al., 2023). For strength and serviceability limit states at room temperature these effects are generally treated implicitly through standard detailing and fabrication rather than explicitly quantified through stress concentration factors. While these assumptions are generally appropriate for ambient-temperature design, their applicability under extreme thermal loading, where material degradation, differential thermal expansion, and instability effects dominate, remains uncertain.

Bridge fires present a fundamentally different loading environment from that assumed in conventional building fire design (Kodur et al., 2010). Fires involving tanker trucks or fuel spills can generate heat release rates and thermal gradients that significantly exceed those associated with standard compartment fires (Song et al., 2024). Steel bridge girders are often directly exposed to flames on multiple sides, experience highly non-uniform temperature distributions along their length and cross sections, and typically lack inherent fire protection. Prior research on steel bridge fires has demonstrated that these conditions can lead to rapid degradation of steel mechanical properties, including reductions in yield strength, elastic modulus, and strain hardening capacity, combined with large thermally induced deformations and restraint forces (Kodur et al., 2017;

Kodur and Gil, 2022). Experimental and numerical studies have shown that such effects can precipitate instability and failure within minutes of fire exposure (Payá-Zaforteza and Garlock, 2012; Peris-Sayol et al., 2015).

Most existing studies on the fire performance of steel bridge girders have focused on global response, such as member deflection, load-bearing capacity, or critical temperature criteria (Kodur et al., 2017). The influence of flange plate thickness transitions on local stress redistribution and instability under fire exposure has not been explored. Under ambient conditions, thickness transitions are well recognized in the fatigue and fracture literature as stress-concentrating details, and they are explicitly treated through fatigue detail categories, transition taper requirements, and weld profiling practices in bridge design and evaluation guidance (Röscher et a., 2023). The extension of this understanding to fire-induced behavior still needs to be investigated.

Recent bridge fire incidents have highlighted the practical importance of this gap in knowledge. The collapse of an I-95 overpass in Philadelphia in 2023 demonstrated the vulnerability of unprotected steel girders to severe fire exposure, with post-event observations suggesting that failure initiated near a transition in bottom flange thickness (Kodur et al., 2024). While such observations are consistent with known fatigue-sensitive detailing issues under ambient conditions, they raise questions on the role of geometric discontinuities in triggering localized instability when combined with severe thermal gradients and temperature-induced degradation.

In fire scenarios, non-uniform heating induces differential thermal expansion both along the girder length and across its cross section, generating localized stresses even in the absence of increased external loading. At flange thickness transitions, mismatches in stiffness between adjacent plate segments can further amplify strain localization, potentially promoting early local yielding, out-of-plane deformation, or local buckling of the thinner flange segment. Such localized failure mechanisms may develop even before global strength (sectional flexural or shear capacities) or deflection limits are reached (Kodur and Naser, 2015).

To address this gap, this study investigates localized failure mechanisms at bottom flange plate thickness transitions in steel bridge girders exposed to fire. The problem is framed explicitly as a local stability issue governed by the interaction of geometric discontinuity, non-uniform thermal expansion, and temperature-dependent material degradation. An advanced coupled thermo-mechanical finite element model is developed to simulate realistic fire exposure conditions, accounting for non-uniform temperature fields, geometric nonlinearity, and degradation of steel properties with temperature.

The objective of this work is to identify the conditions under which flange plate thickness transitions become critical initiation points for localized failure under fire exposure and to clarify the governing mechanisms responsible for this behavior. By emphasizing localized instability rather than global strength loss, the study complements existing fire resistance research and provides insight into failure modes that are not explicitly addressed by current bridge design codes or fire assessment methodologies. The findings are intended to inform performance-based evaluation approaches and detailing strategies aimed at reducing the risk of premature, localized collapse in steel bridge girders subjected to severe fire events.

2. Numerical Modeling Framework

A coupled thermo-mechanical finite element modeling framework is developed using ABAQUS to investigate localized instability at bottom flange plate thickness transitions in steel bridge girders exposed to fire. The framework is formulated to capture the combined effects of fire exposure, temperature-dependent degradation of material properties, and geometric discontinuities, which together govern the initiation and progression of localized failure.

The analysis is conducted in two subsequent steps. First, a transient thermal analysis is performed to compute spatially and temporally varying temperature distributions within the girder under prescribed fire exposure conditions. Second, these temperatures are then mapped onto a nonlinear structural model to simulate the thermo-mechanical response, including stress redistribution, plastic strain development, and localized deformation at elevated temperatures.

This framework has already been validated in other similar studies conducted by the authors on the fire performance of steel structures (Kodur et al., 2024). While the global response of the girder is represented, the numerical framework is specifically applied to investigate the flange thickness transition region. Emphasis is placed on local stress, strain, and deformation behavior in this region to identify mechanisms leading to localized instability under thermal gradients.

2.1 Model Discretization and Meshing

Steel girders are modeled as part of a composite girder-deck system, reflecting typical bridge construction practice. The three-dimensional finite element model is discretized in ABAQUS using thermally coupled eight-node brick elements (C3D8T) for both the steel girder and the concrete deck. Interaction between the steel and concrete components is done using node-to-node tie constraints to simulate full composite action between them.

To accurately capture localized stress and strain development, mesh refinement is applied in the region of the thinner bottom flange and across the flange thickness transition. A coarser mesh is used elsewhere to balance numerical accuracy and computational efficiency. The resulting mesh configuration, including local refinement in the transition region, is illustrated in Figure 2.

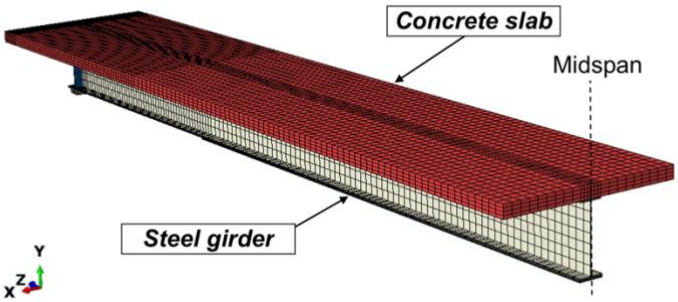

Figure 2: Discretized finite element model of the composite steel girder–concrete deck system

2.2 Temperature-Dependent Material Models

Structural steel is modeled using temperature-dependent thermal and mechanical properties to represent material degradation under fire exposure. Reduction factors for elastic modulus, yield strength, and strain hardening behavior of steel are adopted from Eurocode 3 (Eurocode, 2002), which provides widely accepted constitutive relationships for steel at elevated temperatures.

The mechanical response of steel is represented using an elastoplastic constitutive model with isotropic hardening. Figure 3 presents the resulting stress-strain relationships at selected temperatures, illustrating the progressive reduction in elastic stiffness, yield strength, and post-yield hardening capacity with increasing temperature. At elevated temperatures, the stress-strain curves exhibit a reduced initial slope, lower yield stress, as well as lower strain hardening.

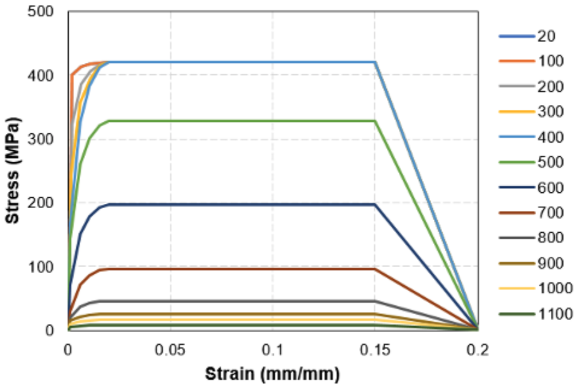

Figure 3: Temperature-dependent stress-strain model for structural steel

Geometric nonlinearity is included to account for large deformation effects arising from thermal expansion and plasticity. This formulation enables the simulation of progressive yielding, plastic strain accumulation, and stiffness degradation under combined thermal and mechanical loading, which are essential for capturing thermally induced deformation and localized instability at the flange thickness transition.

Material fracture or rupture is not explicitly modeled. Instead, the onset of localized instability is identified through the development of concentrated plastic strains, rapid local stiffness degradation, and pronounced localized deformations in the transition region. This approach is consistent with the study objective, which focuses on instability-driven failure mechanisms rather than ultimate material rupture.

2.3 Thermal Boundary Conditions and Fire Exposure

Fire exposure is represented using prescribed temperature-time relationships applied to the exposed surfaces of the girder, using the nominal standard and hydrocarbon fire curves defined in Eurocode 1 (Eurocode, 2002). While the standard fire curve is commonly used to evaluate the fire response of structural members, it may not adequately represent the high temperatures that can be achieved in bridge fire scenarios. For this reason, this study employed both the standard and hydrocarbon curves in order to provide a comparative response between both scenarios.

Convective and radiative heat transfer mechanisms are applied to exposed steel surfaces using the parameters recommended by Eurocode, including representative convection coefficients and surface emissivity values. Unexposed surfaces are assumed to exchange heat with the ambient environment. The resulting transient temperature distributions are transferred to the structural model at each analysis increment, enabling explicit examination of thermal gradient effects on local stress redistribution and deformation behavior without assuming uniform member temperatures or simplified critical temperature limits.

3. Case Study: Bridge Girder with Flange Thickness Transition

A representative composite steel plate girder typical of highway bridge construction is selected as the case study. The girder incorporates a variable bottom flange thickness along its span, reflecting common design practice in which thicker flange plates are provided in regions of higher bending demand to optimize material usage. The case study is intended to identify and isolate the governing mechanisms responsible for localized instability at flange thickness transitions under fire exposure.

3.1 Girder Characteristics

The bridge girder consists of a welded steel plate girder acting compositely with a reinforced concrete deck. The web plate is 12.7 mm thick and 1,092.2 mm deep over the full girder length. The top flange has a constant cross-section, with a thickness of 25.4 mm and a width of 355.6 mm. In contrast, the bottom flange is 406.4 mm wide and varies in thickness along the span: it is 25.4 mm thick over a length of 5.5 m from each support and increases to 50.8 mm in the central region of the girder. The resulting thickness transition in the bottom flange is modeled explicitly. The composite concrete slab is 216 mm-thick and is assumed to have full composite action between the concrete deck and the steel girder. Key geometric details of the girder are shown in Figure 4.

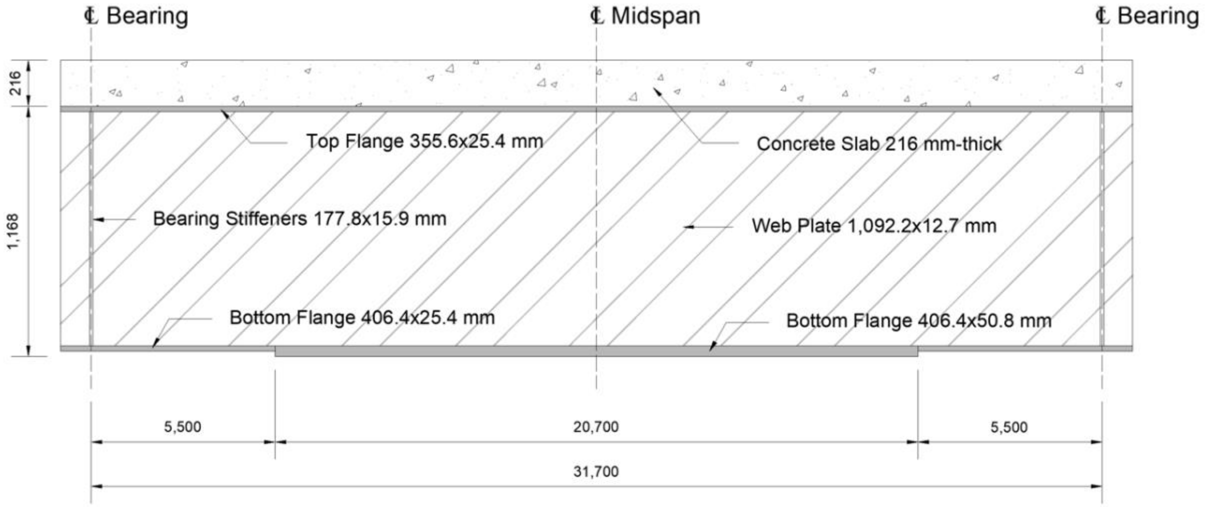

Figure 4: Geometric dimensions of the composite steel plate girder with bottom flange thickness variation

3.2 Fire Exposure and Thermal Response

The thermal response of the composite girder is evaluated under selected fire exposure scenarios. Figure 5 presents the temperature evolution at representative locations within the girder cross-section, including the bottom flange, web mid-depth, top flange, and slab mid-depth. Results show pronounced through-depth thermal gradients. The web experiences the most rapid temperature rise and attains the highest temperatures due to its relatively small thickness and large exposed surface area. The bottom flange also heats rapidly under direct exposure, while the top flange remains comparatively cooler as a result of the insulating and heat-sink effects provided by the concrete slab. Temperatures at the slab mid-depth remain significantly lower than those in the steel components due to the lower thermal conductivity of concrete.

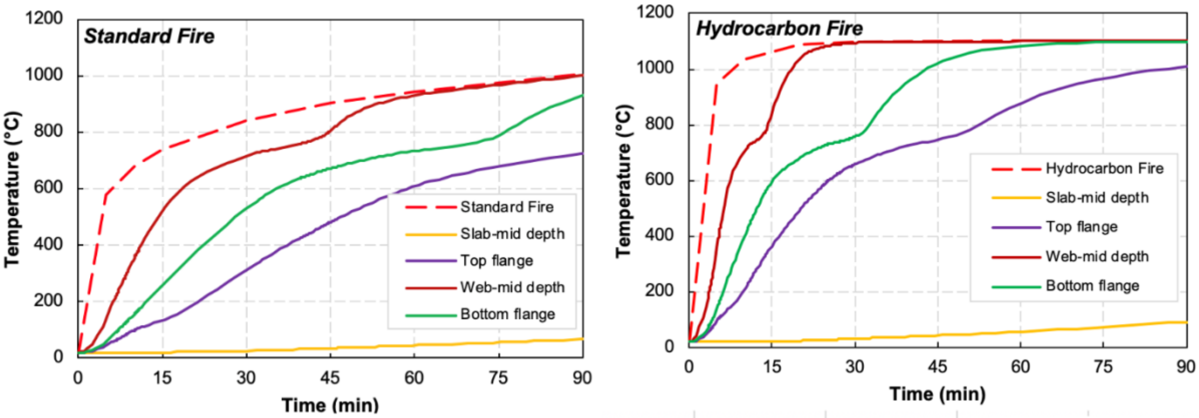

Figure 5: Temperature evolution at selected parts of the composite girder cross-section under standard and hydrocarbon fire exposure

Fire severity strongly influences the magnitude and rate of temperature increase. Under the hydrocarbon fire scenario, steel temperatures rise rapidly and reach substantially higher levels than those observed for the standard fire, which produces more gradual heating and reduced thermal gradients. These results demonstrate the development of significant thermal non-uniformity within the composite section, which directly governs the subsequent thermo-mechanical response examined in the following sections.

3.3 Loading Conditions and Structural Response

The structural response of the composite girder is evaluated under combined mechanical loading and fire-induced thermal effects. The girder is idealized as simply supported and subjected to gravity loading representing its self-weight, increased by 25% to account for superstructure dead load, with no live loads applied during fire exposure. The resulting factored distributed load is 27.5 kN/m, producing a bending moment of 3,452.2 kN·m at midspan, which corresponds to approximately 25% of the girder's plastic moment capacity at ambient temperature.

As temperatures increase, degradation of steel stiffness and strength leads to progressive redistribution of internal forces within the composite section. Differential thermal expansion between the steel girder and concrete slab, together with non-uniform through-depth temperature gradients, induces additional bending moments, axial forces, and localized deformation demands. These effects are most pronounced in regions experiencing steep thermal gradients, particularly in the vicinity of the bottom flange thickness transition.

Figure 6 illustrates the evolution of midspan deflections as a function of fire exposure time under standard and hydrocarbon fire scenarios. The response is characterized by increasing vertical deflections, accumulation of plastic strains in the steel components, and localized stress concentrations near the flange thickness transition. Geometric nonlinearity plays a significant role in this behavior, as large deformations amplify local instability effects under high temperatures.

Although deflection is commonly used as a global indicator of fire response in flexural members, no explicit deflection limit is currently prescribed for bridge girders. The deflection criterion of $L^2/400d$ specified in ASTM E119 (ASTM, 2020) is therefore referenced only as a qualitative benchmark and not as a failure criterion in the present study.

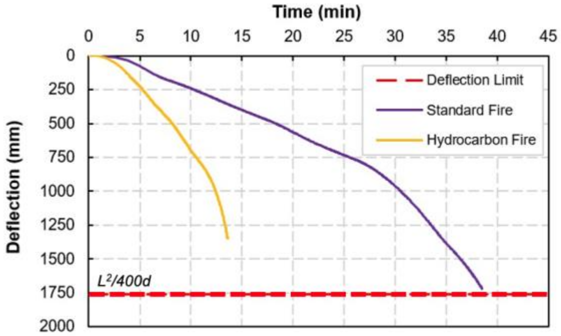

Figure 6: Progression of midspan deflections as a function of fire exposure time

3.4 Observed Failure Mode and Instability Initiation

Across all fire exposure scenarios considered, the girder exhibits a consistent failure mechanism characterized by localized instability initiating at the bottom flange thickness transition. Figure 7 illustrates the development of concentrated plastic strains in the vicinity of the transition between the thinner and thicker bottom flange plates, which governs instabilities for all fire severities.

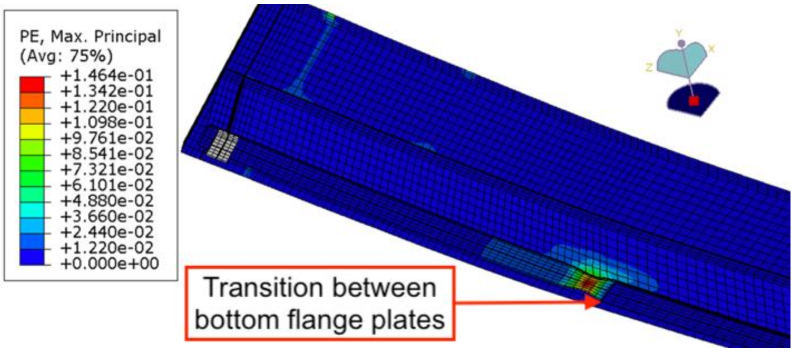

Figure 7: Failure mode observed in the numerical analysis

As fire exposure progresses, degradation of steel stiffness and strength, combined with non-uniform through-depth temperature gradients, leads to increased stresses in the bottom flange. The abrupt change in flange thickness creates a localized stiffness discontinuity, resulting in elevated stress concentrations and reduced local buckling resistance. Once critical temperature levels are reached, plastic strains localize rapidly at the transition region, triggering out-of-plane deformation and local flange buckling.

The observed instability is highly localized and precedes any global flexural or lateral instability of the girder. Although global deflections continue to increase with fire exposure time, failure is governed by the localized loss of load-carrying capacity at the thickness transition rather than by overall member collapse. This behavior highlights the critical role of geometric discontinuities in fire-exposed steel girders and demonstrates that flange thickness transitions can act as preferred initiation sites for thermally induced instability.

These findings indicate that conventional fire resistance assessments based on uniform temperature assumptions or global response measures may not adequately capture localized failure mechanisms associated with flange thickness transitions in steel bridge girders.

4. Implications for Local Stability Under Fire

The results of this study indicate that localized instability at bottom flange thickness transitions can govern the fire-induced response of steel bridge girders, even when global response measures remain within acceptable ranges. These findings highlight the need to explicitly consider local stability effects when evaluating the fire performance of geometrically discontinuous systems. Ongoing research is extending this investigation through additional parametric analyses, with further results to be presented at the conference.

4.1 Flange Thickness Transitions as Stability-Critical Details

The observed response indicates that bottom flange thickness transitions act as stability-critical details under fire exposure. The presence of a stiffness discontinuity promotes localized stress and strain concentration when material degradation and thermal gradients are present. Differential thermal expansion between adjacent flange segments accelerates plastic strain localization in the thinner plate near the transition, leading to instability initiation that is highly localized in nature. Unlike conventional global stability problems in steel girders, such as lateral-torsional buckling, the instability observed here is governed by local geometric discontinuities and amplified by fire-induced effects. This behavior suggests that flange thickness transitions represent a distinct class of fire-induced stability problem that warrants focused consideration in bridge applications.

4.2 Limitations of Global Strength-Based Fire Assessment

Current fire assessment approaches for steel structures commonly rely on global response metrics, such as critical steel temperatures, strength reduction factors, or overall deflection measures. While effective for members with uniform cross sections and relatively uniform thermal exposure, the present results suggest that such approaches may not capture localized instability mechanisms associated with flange thickness transitions. In the cases examined, localized instability consistently initiates prior to global loss of load-carrying capacity or attainment of deflection-based performance limits. As a result, reliance on global response measures alone may underestimate vulnerability in steel bridge girders containing geometric non-uniformities, highlighting the importance of incorporating local response indicators.

4.3 Implications for Design and Assessment Practice

The observed trends suggest that geometric refinements commonly employed for fatigue performance may also influence fire-induced stability, motivating future parametric and experimental investigations. From a design perspective, relatively modest geometric refinements, such as reducing thickness ratios between adjacent flange segments or providing longer, more gradual transition regions, may reduce stiffness discontinuities and delay the onset of localized instability under fire exposure. From an assessment standpoint, the results indicate that performance-based fire evaluations should extend beyond global strength or deflection checks to include localized response measures capable of capturing instability initiation at geometric discontinuities. More broadly, these findings highlight the need to integrate local stability considerations into fire response analyses of bridge structures. Treating fire-induced damage as a localized stability problem, rather than solely a strength degradation issue, provides ground basis for assessing vulnerability and for developing strategies to enhance the fire resilience of steel bridge infrastructure.

5. Conclusions

This study examined localized instability at bottom flange plate thickness transitions in steel bridge girders exposed to fire using detailed coupled thermo-mechanical finite element modeling. The investigation focused on the interaction between geometric discontinuities, non-uniform thermal exposure, and temperature-dependent material degradation, with emphasis on identifying failure initiation mechanisms rather than global collapse behavior.

Based on the results of this study, the following conclusions are drawn:

- The difference in stiffness between adjacent flange segments leads to stress redistribution and plastic strain localization at the transition region as temperatures increase.
- Instability at the thickness transition developed prior to global strength or deflection limit states, demonstrating that local response can control fire resistance.
- Fire severity intensifies differential thermal expansion at thickness transitions, leading to earlier onset of localized buckling compared to uniform heating assumptions.
- Conventional critical-temperature or global capacity checks do not capture the localized instability mechanisms identified in this study and may underestimate vulnerability in steel bridge girders containing geometric discontinuities.

Overall, the results demonstrate that fire-induced damage in steel bridge girders with flange thickness transitions should be treated as a localized stability problem rather than solely global strength and deflection limit states. Future work will focus on expanded parametric investigations considering different solutions already used at ambient conditions (for fatigue), experimental validation of the identified mechanisms, and development of simplified solutions suitable for integration into design practice.

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