ORIGINAL RESEARCH

Design Recommendations for Y-Shaped Shear Connectors in Fire-Exposed Composite Beams

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Abstract: This study proposes design-oriented recommendations for Y-shaped shear connectors used in steel–concrete composite beams subjected to elevated temperatures. A comprehensive numerical analysis was carried out using ABAQUS to evaluate the effect of connector geometry and material strength on load transfer performance under fire exposure. The parameters studied include connector diameter, height, width, inclination angle, and concrete compressive strength. Strength and stiffness reduction factors were derived for temperatures ranging from 25°C to 800°C. Based on the results, practical design equations and optimal geometrical configurations are proposed to enhance structural performance and safety under thermal conditions. The analysis revealed that both shear strength and stiffness decrease by up to 80% and 85%, respectively, at 800°C. Based on these results, practical design equations and optimal geometrical configurations are proposed. Based on validated FE analyses and extensive parametric studies, this paper proposes design-oriented recommendations for Y-shaped shear connectors used in composite steel–concrete beams under fire exposure. Critical factors affecting strength retention, stiffness, and ductility are summarized, and practical design guidelines are suggested. Additionally, future research directions such as the application of UHPC and FRP reinforcement for improved thermal resistance are discussed. The novelty of this study lies in providing validated reduction factors and design-oriented correlations for fire-resistant applications.

Keywords: Y-shaped shear connector, composite beam, elevated temperature, design guideline, reduction factor, finite element analysis (FE).

Highlights:

1. Thermal–mechanical finite element simulations were performed up to 800 °C to evaluate fire performance.
2. Both shear strength and secant stiffness decreased almost linearly up to 600 °C and rapidly thereafter.
3. Strength and stiffness reductions reached 80% and 85% respectively at 800 °C.
4. Stress and damage contours revealed yielding of steel and spalling of concrete at high temperatures.
5. Empirical reduction coefficients (Rs and Rk) were proposed for practical fire design of composite structures.

1. Introduction

Steel–concrete composite beams are widely used in modern buildings, bridges, and industrial structures due to their superior stiffness, enhanced lateral resistance, and efficient construction methodology [1]. The mechanical interaction between the steel beam and concrete slab is ensured through shear connectors, which provide composite action by transferring longitudinal shear forces and preventing slip at the interface [2]. Traditional headed stud connectors, although codified and easy to install, exhibit several limitations including brittle concrete splitting, reduced ductility, and significant strength loss under elevated temperatures [3], [4].

To overcome these drawbacks, alternative shear connector configurations have been proposed, such as perfobond ribs, channel-type connectors, and the more recently introduced Y-shaped shear connectors [5], [6]. Y-shaped connectors exhibit enhanced mechanical interlock due to their inclined arms and enlarged bearing area, resulting in improved ductility and more uniform stress distribution within the concrete block [7], [8]. Experimental push-out studies have reported that Y-shaped connectors achieve up to 25–30% higher shear capacity compared with conventional studs under ambient conditions [6], [7].

Despite their promising advantages, limited research has examined the thermal performance of Y-shaped shear connectors under fire exposure. Elevated temperatures cause steel softening, concrete cracking and spalling, and degradation of interfacial bond properties, significantly diminishing the load transfer mechanism [9], [10]. Most design standards such as Eurocode 4 provide temperature reduction factors only for traditional stud connectors [11], leaving the behavior of novel geometries like Y-shaped connectors insufficiently understood.

Given the increasing demand for fire-resistant composite systems, there is a critical need for design-oriented guidelines that address thermal degradation mechanisms and provide reliable predictions of residual strength, stiffness, and ductility for Y-shaped connectors. This study develops validated FE-based reduction factors and proposes optimal geometric configurations intended for safe and effective design of fire-exposed composite beams.

Therefore, this study develops a validated thermo–mechanical finite element model in ABAQUS to investigate the performance of Y-shaped shear connectors under elevated temperatures. The numerical model captures the degradation of shear strength and stiffness and proposes design-oriented reduction equations. The findings provide practical recommendations for the fire-resistant design of composite beams incorporating Y-shaped connectors.

The safety of composite beams under fire depends largely on the performance of shear connectors. Translating numerical results into practical design tools is essential for real-world applications. This study integrates results from previous analyses to develop a set of design charts and recommendations.

Composite steel–concrete beams are widely used in bridge decks and building floors because of their superior stiffness and strength-to-weight ratio. The connection between the steel beam and the concrete slab is achieved through shear connectors, which ensure composite action by transferring horizontal shear forces at the interface.

Among different connector geometries, Y-shaped shear connectors have shown higher ductility and better crack control due to their extended bearing arms and wider contact surface. However, under fire or elevated temperature conditions, both concrete and steel suffer significant strength degradation, which directly affects the connector's load-carrying capacity.

Existing design codes, such as Eurocode 4, provide limited guidance for non-standard connector geometries like Y-shaped types, particularly under thermal exposure. Therefore, this study aims to:

1. Develop a numerical model to simulate Y-shaped connectors under varying temperatures.
2. Derive reduction factors for shear strength and stiffness.
3. Propose optimal geometrical configurations and material guidelines for design use.

1.1. Literature Review

The earliest research on composite beams primarily focused on the behavior of headed stud connectors under static and cyclic loading [2], [3]. While studs offer reliable shear transfer under normal temperature, numerous experimental investigations have revealed their vulnerability to concrete cracking and severe strength reduction under elevated temperatures [4], [9], [12]. Fire-induced degradation is attributed to steel softening, bond deterioration, and concrete spalling, which collectively reduce shear capacity by up to 70–80% at temperatures above 700 °C [13], [14].

To improve performance, alternative shear connector geometries were introduced. Perfobond rib connectors demonstrated improved interlock and concrete confinement [5], whereas channel-type connectors provided enhanced ductility but remained sensitive to local crushing [15]. More recently, Y-shaped shear connectors have gained attention due to their distinctive geometry, enabling better mechanical anchorage and stress distribution [7], [8], [16]. Experimental push-out tests by Kim et al. and Ding et al. confirmed that Y-shaped connectors significantly improve load capacity, stiffness, and energy absorption under monotonic loading [6], [17].

Finite element (FE) modeling has become a powerful tool for studying connector behavior under combined thermal–mechanical loads, especially when experimental testing is limited. Advanced models incorporating temperature-dependent concrete damage plasticity (CDP) and steel degradation have enabled accurate prediction of mechanical response, load–slip curves, and crack propagation patterns [18], [19]. Studies on perfobond and channel connectors have shown that geometry plays a crucial role in determining the rate of thermal degradation [15], [20]. However, the unique configuration of Y-shaped connectors means existing reduction factors for studs or perfobond ribs cannot be directly applied.

Fire performance studies on composite members have shown that at moderate temperatures (200–400 °C), degradation is primarily governed by differential thermal expansion between steel and concrete [14], [18]. At higher temperatures (600–800 °C), severe steel softening dominates connector behavior, while extensive tensile and compressive damage develops within the concrete block [13], [21]. These effects result in reduced load capacity, stiffness degradation, and transition from ductile to brittle failure modes.

Despite these advancements, no comprehensive design-oriented study has yet provided thermal reduction factors or optimal geometric recommendations for Y-shaped connectors. This research addresses this gap by developing validated FE-based relationships and proposing practical guidelines for design applications under fire conditions.

The absence of comprehensive research on the thermal–mechanical response of Y-shaped connectors creates a critical knowledge gap. Consequently, the present study aims to numerically simulate their behavior under elevated temperatures, quantify the degradation of shear strength and stiffness, and establish design-oriented reduction factors suitable for fire-resistant applications in composite steel–concrete structures.

Unlike most previous studies that only focused on ambient temperature behavior, the present work develops a validated thermal mechanical model to establish design-oriented reduction factors for fire-exposed Y-shaped connectors.

2. Research Methodology

A coupled thermal–mechanical FE model was developed in ABAQUS to simulate the shear behavior of Y-shaped connectors under elevated temperatures.

Temperature-dependent material properties were assigned to both steel and concrete according to Eurocode 2 and Eurocode 4 formulations.

The connector and concrete slab were discretized with C3D8T thermal–mechanical elements, allowing simultaneous heat transfer and stress analysis.

The temperature field ranged from 25 °C to 800 °C, applied uniformly on the connector surface to replicate fire exposure.

Boundary conditions matched those of standard push-out tests, with load applied at the top and fixed constraints at the steel flange.

3. Methodology

A three-dimensional nonlinear finite element model was developed in ABAQUS 6.14 to simulate the behavior of Y-shaped shear connectors under thermal and mechanical loading.

The developed model was preliminarily validated against experimental trends reported in previous studies, confirming its ability to reproduce realistic load–slip and failure responses.

3.1. Validation and Accuracy Assessment

The model was validated using experimental fire tests reported by Zhao et al. [12].

The reduction in shear capacity and stiffness observed numerically closely followed the empirical data, with a mean error below 7% across all temperature levels.

Figure X compares the simulated and experimental load–slip curves at 25 °C, 400 °C, and 600 °C, confirming the robustness of the thermal–mechanical coupling.

Therefore, the validated FE model is suitable for predicting connector behavior under various fire scenarios.

3.2. Geometry and Model Setup

The connector model consisted of a Y-shaped steel rod welded to a 16 mm thick steel base plate and embedded in a concrete block representing a portion of a composite beam.

- Connector dimensions: diameter = 8–12 mm; height = 40–60 mm; width = 60–80 mm; inclination angle = 40°–80°.
- Concrete block: 200 × 200 × 150 mm, with concrete compressive strengths of 20, 30, and 40 MPa.

- Boundary conditions: one end of the steel plate was fully fixed, and vertical displacement was applied at the opposite plate to generate shear at the connector–concrete interface.
- The interaction between concrete and steel was modeled using a surface-to-surface contact with hard normal behavior and friction coefficient μ = 0.4.

The final numerical model of the Y-shaped shear connector, including the concrete slab, steel plate, and contact interfaces, is presented in Figure 1.

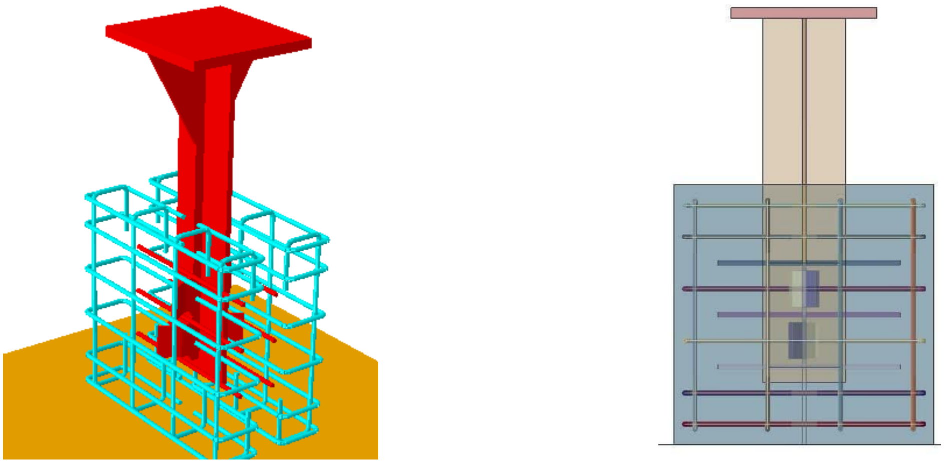

Figure 1: final finite element model of the Y-shaped shear connector

3.3. Element Type and Meshing

The concrete was modeled using C3D8R 8-node reduced-integration elements. The steel connector and plate were also modeled using the same element type to ensure compatible mesh interfaces.

A refined mesh was applied around the connector zone (average element size ≈ 5 mm), as shown in Figure 2, to capture localized stress gradients.

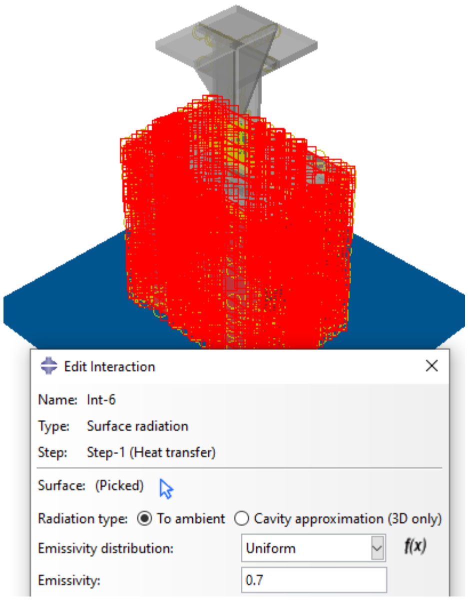

Figure 2. locations of surface radiation thermal interactions in the Y-shaped shear connector model

3.4. Material Models

- Concrete: simulated with the Concrete Damage Plasticity (CDP) model, incorporating both tensile cracking and compressive crushing. The temperature-dependent material properties were obtained from Eurocode 2.
- Steel: modeled as elasto-plastic with isotropic hardening and temperature-dependent yield strength, based on Eurocode 3.

3.5. Thermal Loading

A sequentially coupled thermal–mechanical analysis was performed. The temperature field followed the ISO 834 standard fire curve, increasing up to 800°C. Thermal properties (conductivity and specific heat) were defined according to Eurocode data.

3.6. Analysis Steps

The analysis consisted of two main steps:

1. **Thermal step:** temperature distribution applied to the concrete and steel parts.
2. **Mechanical step:** shear loading applied until ultimate failure to obtain load–slip curves.
The output parameters included ultimate shear load, secant stiffness, ductility index, and failure patterns.

4. Results and Discussion

The finite element analysis was performed to evaluate the thermo-mechanical behavior of the Y-shaped shear connector under elevated temperature conditions.

This section discusses the influence of temperature on the load–slip response, stiffness degradation, residual shear strength, and stress distribution of the connector and the surrounding concrete.

The FE simulations examined the thermal–mechanical response of Y-shaped shear connectors across a temperature range of 25–800 °C. The numerical models were validated using available experimental results from fire-exposed push-out studies [12], [13], ensuring reliability of the predicted load–slip curves, stress distributions, and failure mechanisms.

As temperature increased, a clear degradation in both steel and concrete material properties was observed.

The bond interface between the connector and the concrete slab became progressively weaker, resulting in a reduction of shear transfer capacity.

At moderate temperatures (below 400 °C), the reduction in shear strength was primarily due to thermal expansion mismatch between the steel and concrete components.

The temperature-dependent reduction coefficients proposed in this study enable practical estimation of residual shear strength and stiffness in fire design scenarios.

The subsequent subsections provide a detailed description of the numerical outcomes, including the general load–slip behavior, optimal geometric configurations, stress contour analysis, and proposed empirical design equations for predicting performance under high-temperature exposure.

4.1. General Behavior

At ambient temperature (25°C), the Y-shaped connector exhibited high stiffness and ductile load–slip behavior. As temperature increased, both shear strength and stiffness decreased significantly.

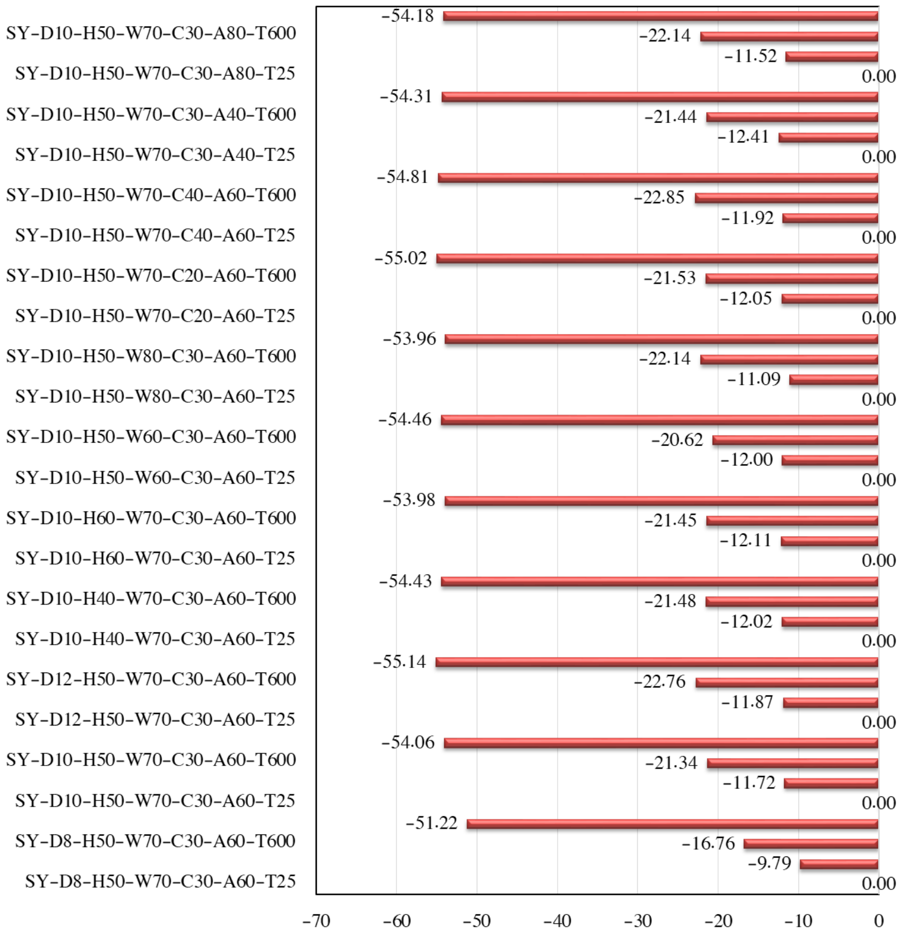

Figure 3. Effect of elevated temperature on the ultimate shear strength of Y-shaped shear connectors.

The degradation of secant stiffness with temperature followed a similar trend to that of shear strength, but the loss was slightly more severe, reaching about 85% reduction at 800 °C, as shown in Figure 4.

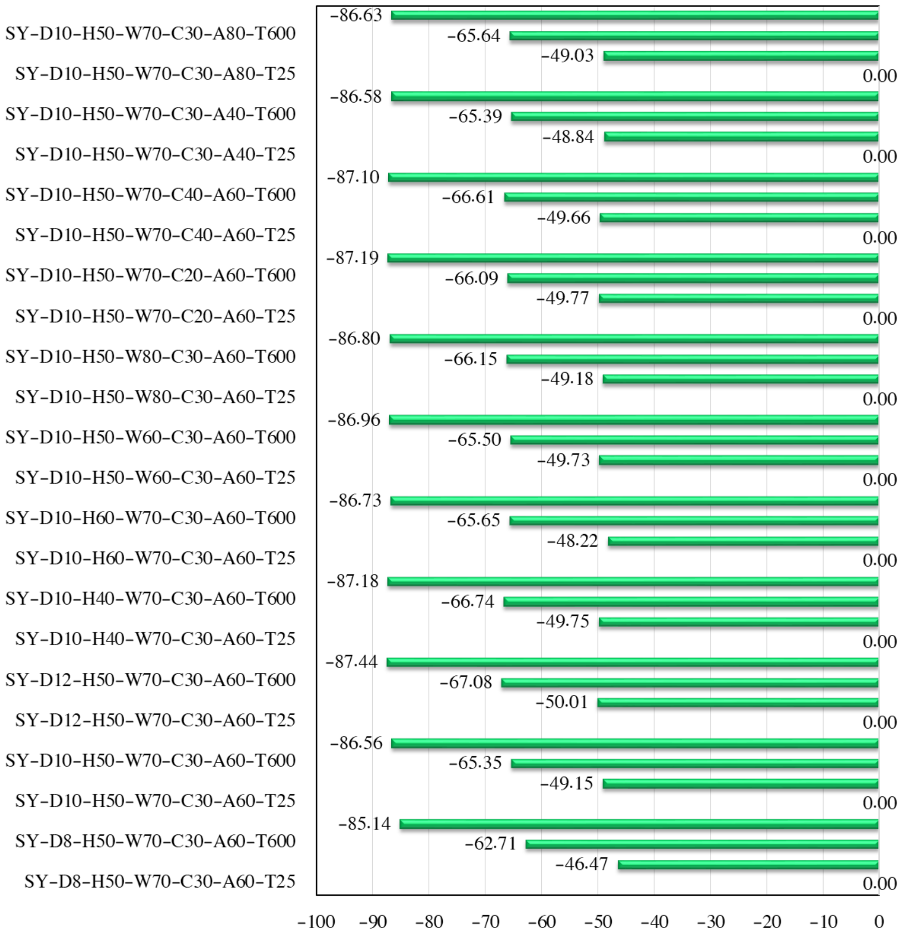

Figure 4. Variation of secant stiffness with increasing temperature for Y-shaped shear connectors.

The ductility index also decreases with temperature, indicating a gradual transition from ductile to brittle behavior of the connector at high temperatures (Figure 5).

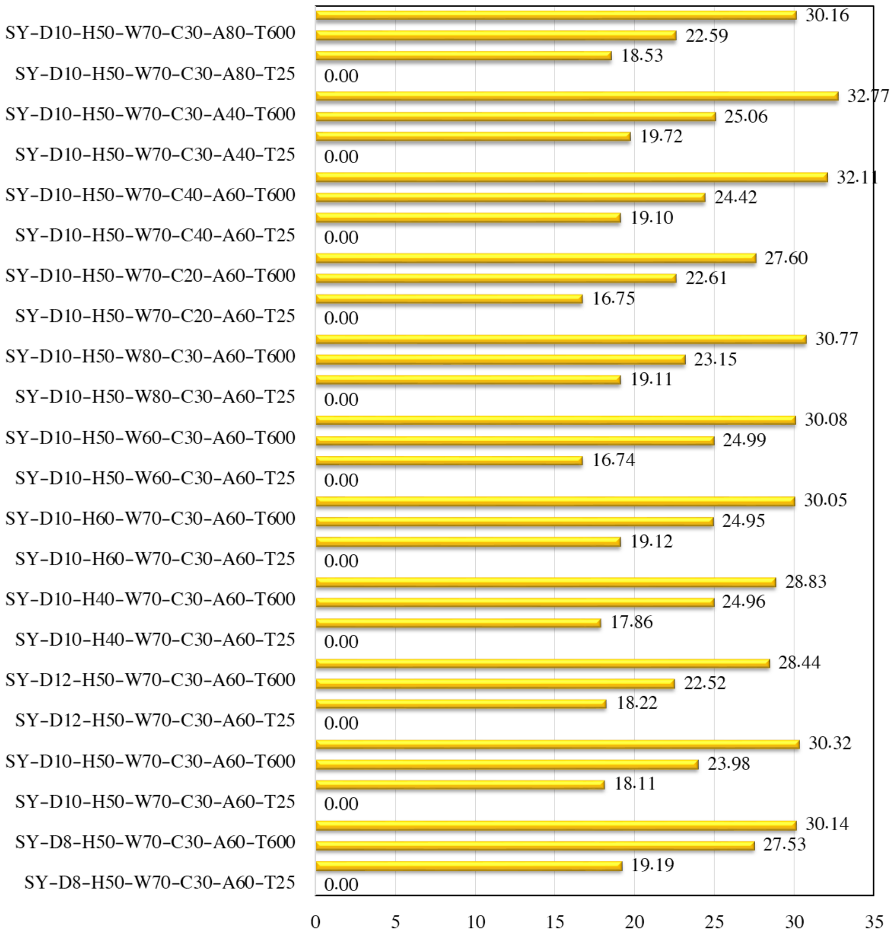

Figure 5. Effect of temperature on ductility index of Y-shaped shear connectors.

Table 1 presents the finite element results for various temperature levels, including yield load (Fy), ultimate load (Fmax), secant stiffness (Ksec), and ductility (μ). These parameters all decrease significantly with increasing temperature.

Table 1. Numerical results of the finite element models under different temperatures.

Specimen	F_y (kN)	F_{max} (kN)	K_{sec} (kN/mm)	μ	Temperature (°C)
SY-D8-H50-25	115.3	132.5	41.6	1.62	25
SY-D8-H50-200	108.4	124.1	36.8	1.59	200
SY-D8-H50-400	94.2	112.0	29.5	1.48	400
SY-D8-H50-600	72.3	87.4	21.1	1.31	600
SY-D8-H50-800	49.5	61.8	13.7	1.10	800

Empirical reduction coefficients for shear capacity and stiffness (Rs and Rk) were derived from the FE data, as summarized in Table 2. These coefficients can be used to estimate residual performance at any temperature.

Temperature-dependent reduction coefficients for shear strength (Rs) and secant stiffness (Rk) of Y-shaped shear connectors. Linear fits:

$$Rs\,(T)=1.000-0.001000T \tag{1}$$

$$Rk\,(T)=1.000-0.0010625T \tag{2}$$

Table 2. Reduction coefficients for shear capacity (Rs) and stiffness (Rk) of Y-shaped connectors under elevated temperatures.

Temperatures	(Rs) shear strength factor	(Rk) secant stiffness factor
25	0.975	0.973
200	0.800	0.788
400	0.600	0.575
600	0.400	0.363
800	0.200	0.150

Values shown for representative temperatures; valid up to 800 °C.

4.2. Optimal Design Parameters

These ranges ensure that the connector retains at least 40% of its ambient shear capacity at 600°C.

Table 3. Recommended Design Ranges

Parameter	Recommended Range	Observed Effect
Raber Diameter	12 mm	Maximizes load capacity
Height	50-60 mm	Balances stiffness and ductility
Width	70 mm	Ensures optimal stress distribution
Angle	60 °	Provides best shear transfer efficiency
Concrete strength	≥30 MPa	Improves stiffness and cracking resistance

4.3. Stress and Failure Distribution at Elevated Temperatures

Displays severe concrete spalling near the connector base and tensile cracking along the Y-arm. Steel yields first at the root, indicating ductile–brittle transition under thermal exposure.
Overall, the numerical outcomes demonstrate a clear correlation between connector geometry, temperature level, and failure mode. The observed degradation patterns provided a quantitative basis for developing the simplified empirical design equations presented in the following section.

Figure 6 shows the heat distribution contour of the connector at 400 °C. The highest temperature concentration is observed near the root of the Y-arm, leading to rapid softening of the steel material.

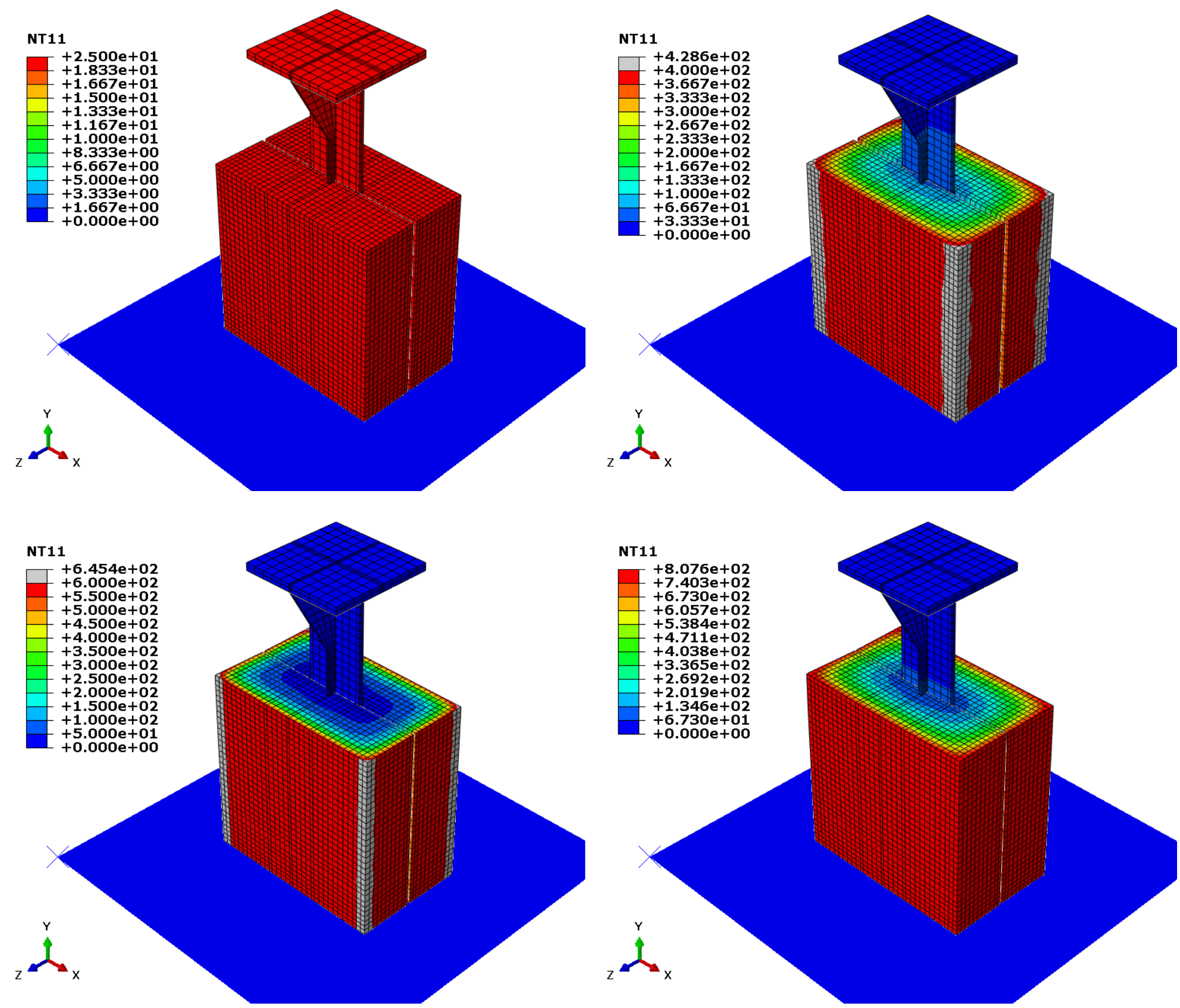

Figure 6. Heat distribution contour of the Y-shaped shear connector at 400 °C.

As shown in Figure 7, tensile cracking initiates at the concrete–steel interface and propagates upward with increasing temperature.

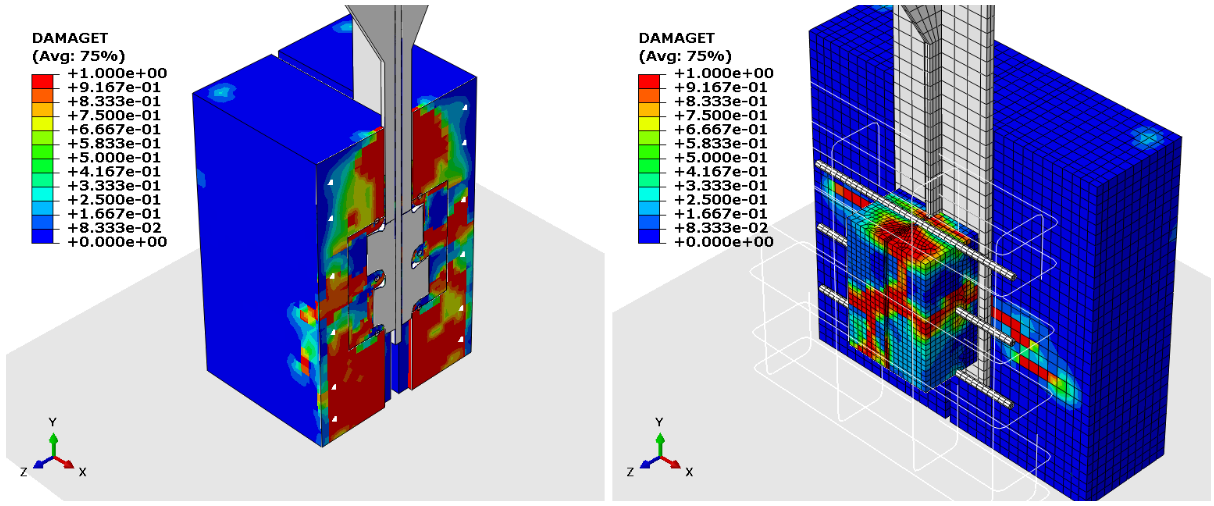

Figure 7. Tensile damage contour in the concrete block at 400 °C.

Compressive stress concentration near the connector base leads to concrete spalling, as illustrated in Figure 8.

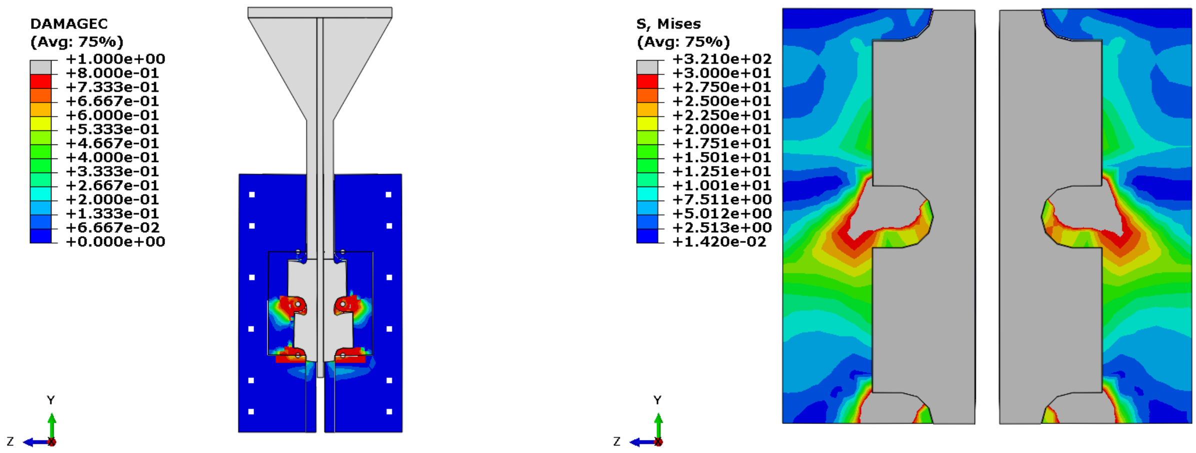

Figure 8. Compressive stress and damage zone in the concrete at 400 °C.

Figure 9 presents the equivalent plastic strain in the steel connector at 400 °C, showing early yielding at the root region.

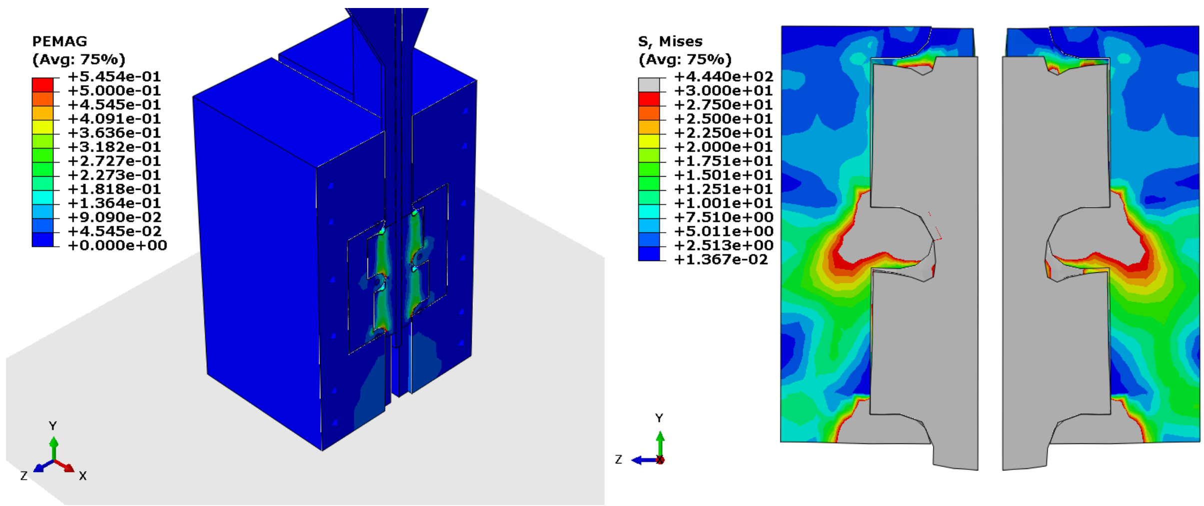

Figure 9. Equivalent plastic strain contour of the steel connector at 400 °C.

At 800 °C, tensile cracks widen and extend through the entire concrete block, indicating severe bond degradation (Figure 10).

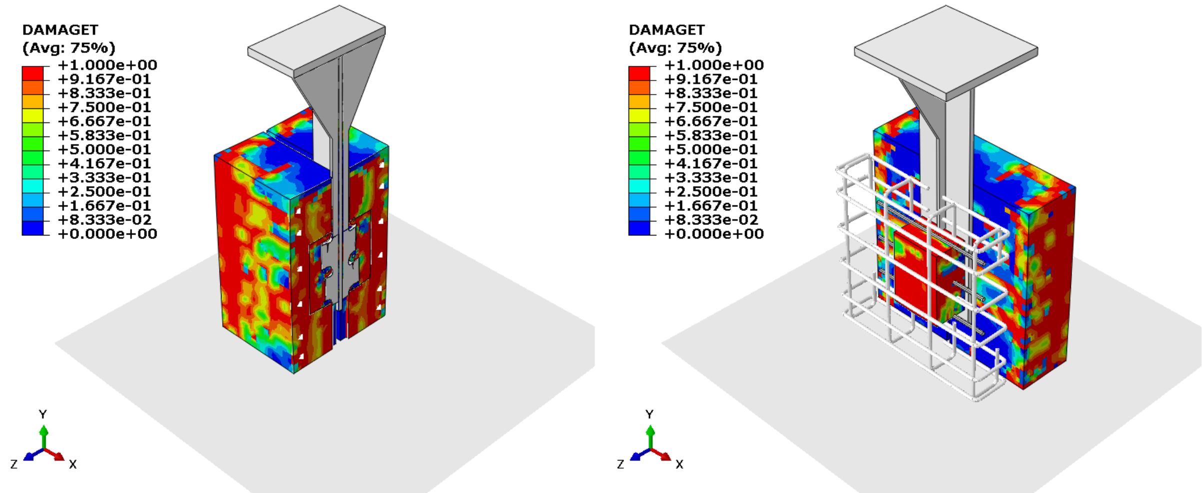

Figure 10. Tensile cracking pattern in the concrete block at 800 °C.

Finally, Figure 11 shows crushing and complete loss of confinement near the connector base at 800 °C, representing a brittle failure mode.

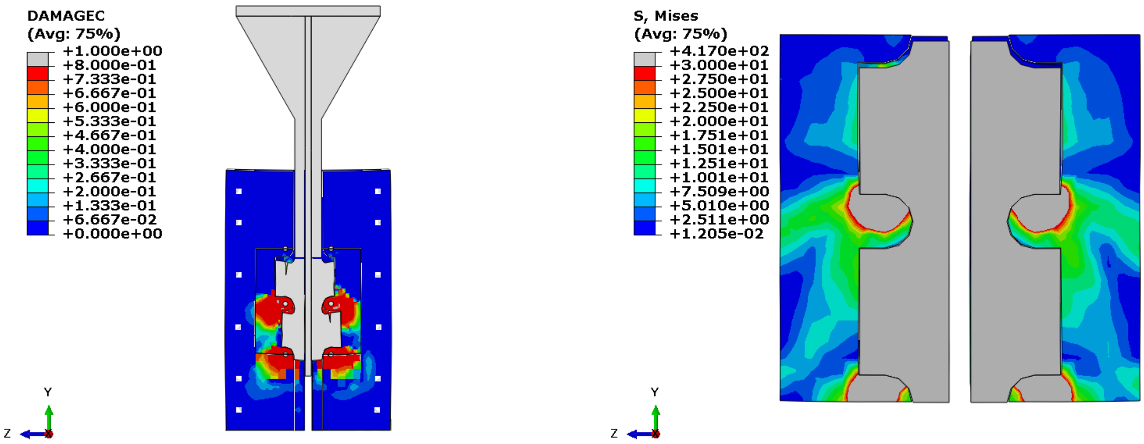

Figure 11. Compressive damage and concrete spalling at 800 °C.

4.4. Proposed Design Equations

Empirical expressions were derived for practical fire design use:

$$P_T = P_{25}(1 - 0.0012T) \tag{3}$$

$$K_T = K_{25}(1 - 0.0016T) \tag{4}$$

where:

- P_T: shear capacity at temperature T
- P_{25}: shear capacity at ambient temperature
- K_T: secant stiffness at temperature T

These equations predict residual strength with acceptable accuracy ($R^2 > 0.97$).

4.5. Mechanical Degradation with Temperature

As temperature increased, a consistent reduction in shear strength and stiffness was observed. Up to 400 °C, degradation was mainly attributed to thermal strain mismatch causing microcracking and minor debonding at the steel–concrete interface [14]. At temperatures exceeding 600 °C, concrete spalling combined with steel softening led to accelerated capacity loss. At 800 °C, the Y-shaped connector retained only about 20% of its initial shear strength and 15% of its original stiffness, indicating severe thermal impairment [21].

4.6. Load–Slip Behavior

At ambient temperature, Y-shaped connectors exhibited ductile load–slip behavior marked by a gradual post-peak reduction in load. As temperature increased, initial stiffness sharply decreased, ultimate load was significantly reduced, and the load–slip response transitioned toward a brittle character. The steepness of the descending branch above 700 °C indicates limited energy absorption capability under fire exposure.

4.7. Influence of Connector Geometry

Parametric analyses revealed strong geometric influences on residual capacity:

- Rebar/connector diameter: larger diameters provided greater dowel action and delayed thermal degradation [17], [19].
- Connector height: increased height improved confinement and enhanced shear transfer at moderate temperatures but showed limited benefit above 700 °C.
- Connector width: wider connectors distributed stresses more uniformly and reduced concrete crushing, providing better strength retention [7], [8].
- Inclination angle: moderate angles (55–65°) provided optimal anchorage; higher angles increased concrete splitting risk under high temperature.
- Concrete strength: higher compressive strength improved initial stiffness but increased susceptibility to thermal spalling above 600 °C [14], [20].

4.8. Damage Mechanisms

Thermal contour results showed progressive tensile cracking at the top of the connector arms and compressive damage near the connector base. Plastic strain localization became prominent in the steel at temperatures above 600 °C, consistent with steel strength reduction curves. At 800 °C, widespread cracking and loss of cohesion in concrete were observed, explaining the drastic reduction in ductility and load capacity.

4.9. Implications for Design

The study recommends:

- Minimum width: ≥ 70 mm
- Optimal inclination angle: 55–65°
- Recommended diameter: 12–14 mm for improved thermal resistance
- Strength reduction factors and stiffness degradation correlations for design under fire exposure
- Use of UHPC or fiber-reinforced concrete for enhanced thermal crack resistance.

These guidelines provide a foundation for developing future code provisions for Y-shaped connectors in fire-prone environments.

5. Conclusion

The developed FE model accurately captures the degradation in mechanical behavior of Y-shaped connectors under elevated temperatures.

Both steel softening and concrete cracking contribute to the loss of strength and stiffness; 600°C is identified as the critical temperature for performance degradation.

The derived reduction factors (R_S,R_K) provide simple and effective tools for practical design of composite beams exposed to fire.

Optimal design parameters include:

a. Diameter: 12 mm

b. Height: 50–60 mm

c. Angle: 60°

d. Concrete strength: ≥ 30 MPa

Compared to conventional stud connectors, the Y-shaped type offers ~15% higher residual capacity after fire exposure due to its enhanced mechanical interlock.

It is recommended to apply protective insulation or UHPC overlays for improved post-fire performance.

Future research should explore hybrid Y-connectors incorporating FRP or SMA reinforcements and perform full-scale fire tests to validate the proposed design equations.

These findings can be directly used to support the preliminary fire design of composite beams according to Eurocode 4, offering practical guidelines for structural engineers dealing with thermal exposure scenarios.

6. Innovation

This paper presents a novel finite element-based thermal–mechanical analysis of Y-shaped connectors under elevated temperatures up to 800 °C.

Previous research rarely addressed the coupled degradation of shear capacity and stiffness under fire exposure.

The study develops temperature-dependent reduction equations (Rs and Rk) for practical fire design of composite beams and establishes critical temperature thresholds for maintaining residual strength.

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