

# Finite Element Investigation of Stiffness-Controlled Shear Connector Behavior in Composite Slab–Girder Systems

Eisa Khan <sup>1</sup>, Abdullah Ajeel <sup>1</sup>, Hafiz Ahmed Waqas <sup>1,\*</sup> and Kong Fah Tee <sup>2,\*</sup>

<sup>1</sup> Department of Civil Engineering, Ghulam Ishaq Khan Institute of Engineering Sciences and Technology- Topi 23640, Pakistan

<sup>2</sup> Department of Civil and Environmental Engineering, King Fahd University of Petroleum & Minerals (KFUPM), Dhahran Saudi Arabia

\* Correspondence: [hafiz.waqas@giki.edu.pk](mailto:hafiz.waqas@giki.edu.pk), [tee.fah@kfupm.edu.sa](mailto:tee.fah@kfupm.edu.sa)

## Abstract

This study presents a three-dimensional finite element investigation of a composite slab–girder system with emphasis on the mechanical response of different shear connector configurations. The numerical model consists of a reinforced concrete slab with a compressive strength of 40 MPa, an I-shaped steel girder, reinforcement mesh, headed stud connectors, and removable bolted connectors. All steel components were initially modeled using A36 steel properties, while higher-strength and higher-stiffness materials were later assigned to the connectors and nuts as part of parametric study. The connectors were uniformly spaced at 150 mm along the span to ensure consistent composite interaction. The analysis focused on stress distribution, force transfer mechanisms, and stiffness-controlled load sharing within the composite system. The results demonstrate that connectors with higher stiffness and strength attract significantly greater stress than more flexible alternatives due to deformation compatibility and stiffness-based force redistribution inherent in finite element formulations. Although stiffer connectors enhance overall composite action, they also introduce localized stress concentrations that may govern fatigue performance or initiate failure. These findings highlight the importance of considering connector stiffness alongside strength in composite design. Overall, the study provides valuable insight into optimizing shear connector selection and supports the development of composite systems that achieve an improved balance between strength, ductility, and stress efficiency.

**Keywords:** Shear studs, Composite beam, Finite element analysis, ABAQUS, Shear connectors, Parametric study, Connector stiffness, Structural performance.

## 1. Introduction

Composite slab girder systems are extensively used in modern civil engineering structures due to their high structural efficiency, improved stiffness, and effective material utilization. The composite action between the concrete slab and steel girder is primarily governed by the performance of mechanical shear connectors, which enable force transfer across the steel–concrete interface and control slip behavior. Consequently, the mechanical properties, geometry, and stiffness of these connectors play a critical role in the overall response of composite systems under service and ultimate loading conditions.

Previous research has shown that connection detailing and reinforcement strategies significantly influence stress distribution, deformation capacity, and structural

robustness. Studies on reinforced concrete and steel–concrete connections have demonstrated that stiffness compatibility at joint and interface regions governs force redistribution and damage progression [1], [2]. Investigations into hybrid and advanced material systems further indicate that increasing material stiffness at localized regions may lead to higher stress demand, even when global strength capacity is enhanced [3]. Similarly, experimental and numerical studies on steel connections have highlighted the sensitivity of stress concentration to connector geometry and material properties, particularly under cyclic or displacement-controlled loading [4].

In composite beam systems, several researchers have emphasized the importance of considering shear slip and partial interaction effects. Subsequent analytical and numerical studies [5] established that force sharing among connectors is primarily stiffness-driven rather than strength-driven. Finite element investigations have further confirmed that stiffer connectors attract higher internal forces due to deformation compatibility, which may govern fatigue life or localized failure even when ultimate strength requirements are satisfied [6], [7]. Design standards such as AISC 360-22 and Eurocode 4 therefore recommend ductile connector behavior to allow stress redistribution and prevent brittle failure modes.

Despite the extensive literature on strength-based design of shear connectors, limited attention has been given to the effect of connector stiffness variation on stress redistribution in composite slab–girder systems subjected to localized imposed deformation. In particular, the influence of high-strength and high-stiffness fasteners on stress attraction under displacement-controlled loading remains insufficiently explored. To address this gap, the present study develops a detailed three-dimensional finite element model of a composite slab–girder system with pinned boundary conditions at both ends. A prescribed vertical deformation of 100 mm is applied over a 50 mm wide strip at two symmetric locations positioned 2000 mm from each support. A parametric study is conducted by varying the material properties of shear connectors to investigate stiffness-controlled stress transfer mechanisms and their implications for composite behavior.

## 2. Materials and Methods

### 2.1 Geometry and Structural Configuration

The composite system comprises a 1000 mm × 6000 mm reinforced concrete slab connected to a 6000 mm long I-shaped steel girder with a depth of 1000 mm. The slab is reinforced with a 5 mm diameter steel mesh at 100 mm × 100 mm spacing. Composite action is achieved using headed studs (20 mm top diameter, 10 mm bottom diameter) and removable bolted connectors (30 mm clipper, 15 mm screw), uniformly spaced at 150 mm. The girder is modeled with pinned support at both ends, allowing rotation while restraining translation. This configuration ensures realistic representation of global bending and interface shear behavior, fig 2. Shows the details of the dimensions. Fig 1. Show the assembly of the whole model.

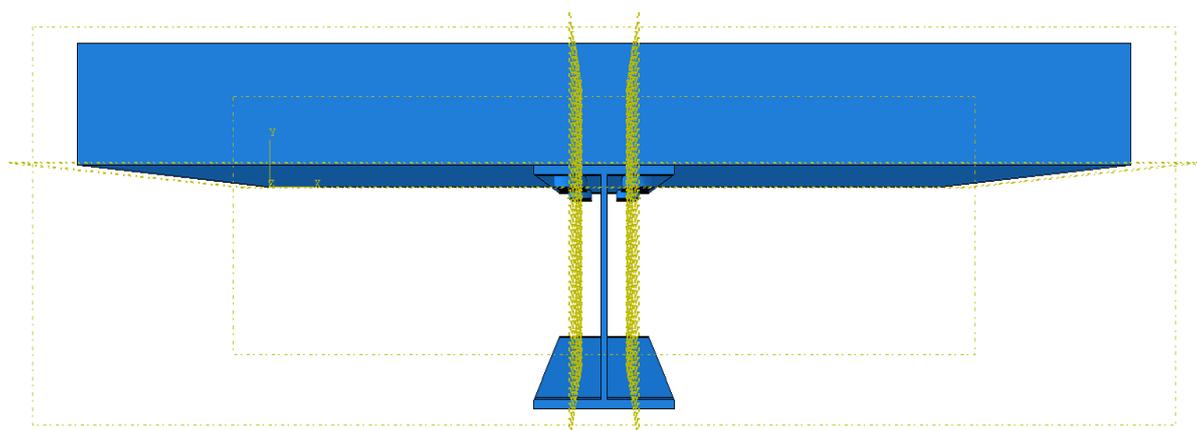


Figure 1: Assembly of the slab girder composite system.

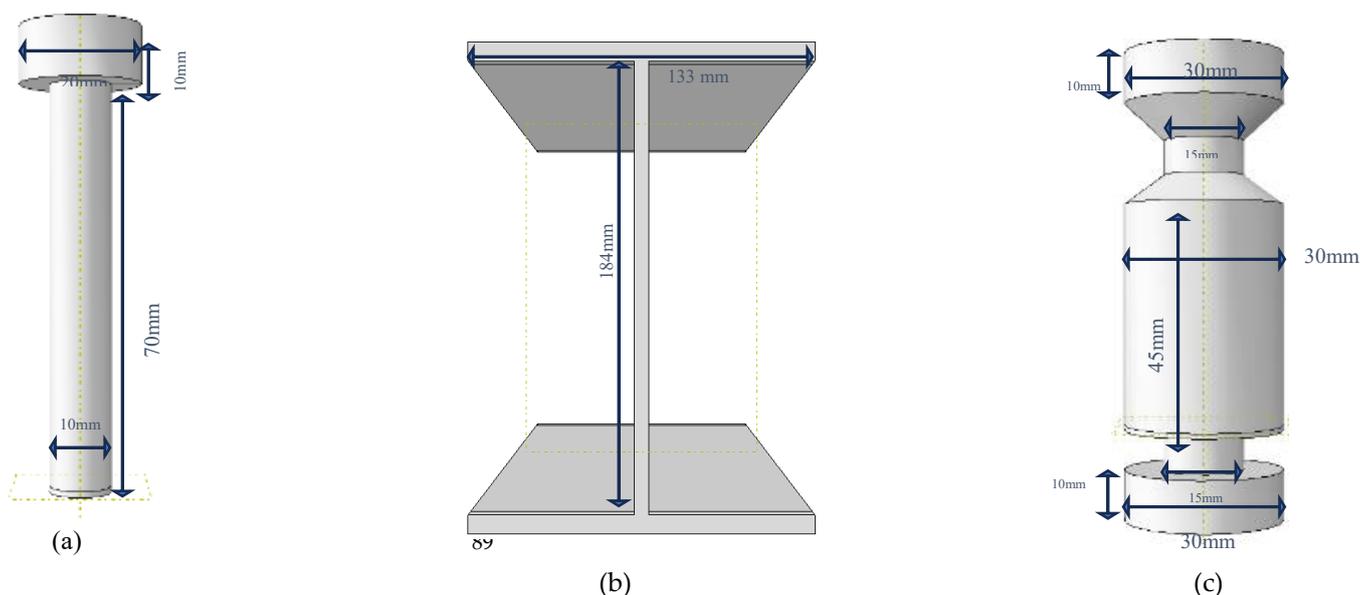


Figure 2 (a) Head studs, (b) girder, & (c) removable bolts dimensions

### 2.2 Material Modelling

The concrete slab is modeled as a homogeneous material with a compressive strength of 40 MPa, assuming isotropic elastic behavior up to the service range. The steel girder

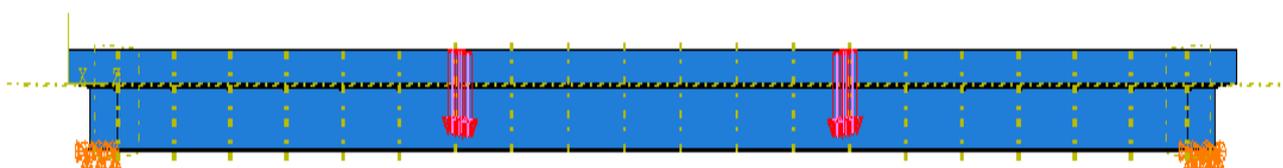
and reinforcement mesh are assigned A36 steel properties with an ultimate tensile strength of 420 MPa. Headed studs and bolted connectors are modeled using elastic plastic material definitions, where alternative material properties are assigned during parametric study to represent varying strength and stiffness levels. Head stud mechanical properties were adopted from ASTM A193/A193M (Table 2), mild steel properties from ASTM A36/A36M (Table 2), and high-strength alloy steel properties from EN 10083-3 (Table 3) for 42CrMo4 in the quenched and tempered condition. All steel components are assumed to exhibit linear elasticity prior to yielding, and material nonlinearity is considered through stress strain relationships to capture stiffness-dependent force redistribution, table-1 shows the alternative material properties of the bolts and studs.

**Table 1 Alternative material properties**

Sl.No	Material	Common Standard	Ultimate Tensile Stress (MPa)	Yield Stress (MPa)	Ultimate Strain ( $\epsilon_u$ )
1	Mild Steel Stud	ASTM A36 / C20	400	~250	0.20 – 0.25
2	Carbon Steel Stud	ASTM A193 B7	860	$\geq 720$	0.12 – 0.15
3	Alloy Steel Stud	42CrMo4 (DIN 1.7225)	900	850	0.10 – 0.14
4	High-Strength Stud	ARP 8740	~1250	~1050	0.07 – 0.10
5	Ultra-High-Strength Stud	ARP2000	~1400	~1200	0.06 – 0.08

**2.3 Boundary Conditions and Loading**

The composite slab-girder system is modeled with pinned supports at both ends of the steel girder, allowing rotational freedom while restraining translational movement. This simulates a simply supported configuration, ensuring realistic bending behavior under applied loads. A prescribed vertical displacement of 100 mm is applied over a 50 mm wide loading strip at two symmetric locations, positioned 2000 mm inward from each support. This displacement-controlled loading induces bending and interface shear within the slab-girder assembly. All connectors and reinforcement are assumed fully bonded to maintain composite action, allowing evaluation of stress redistribution under varying connector stiffness and strength, fig 3. Represents the visuals of boundary conditions.



(a)

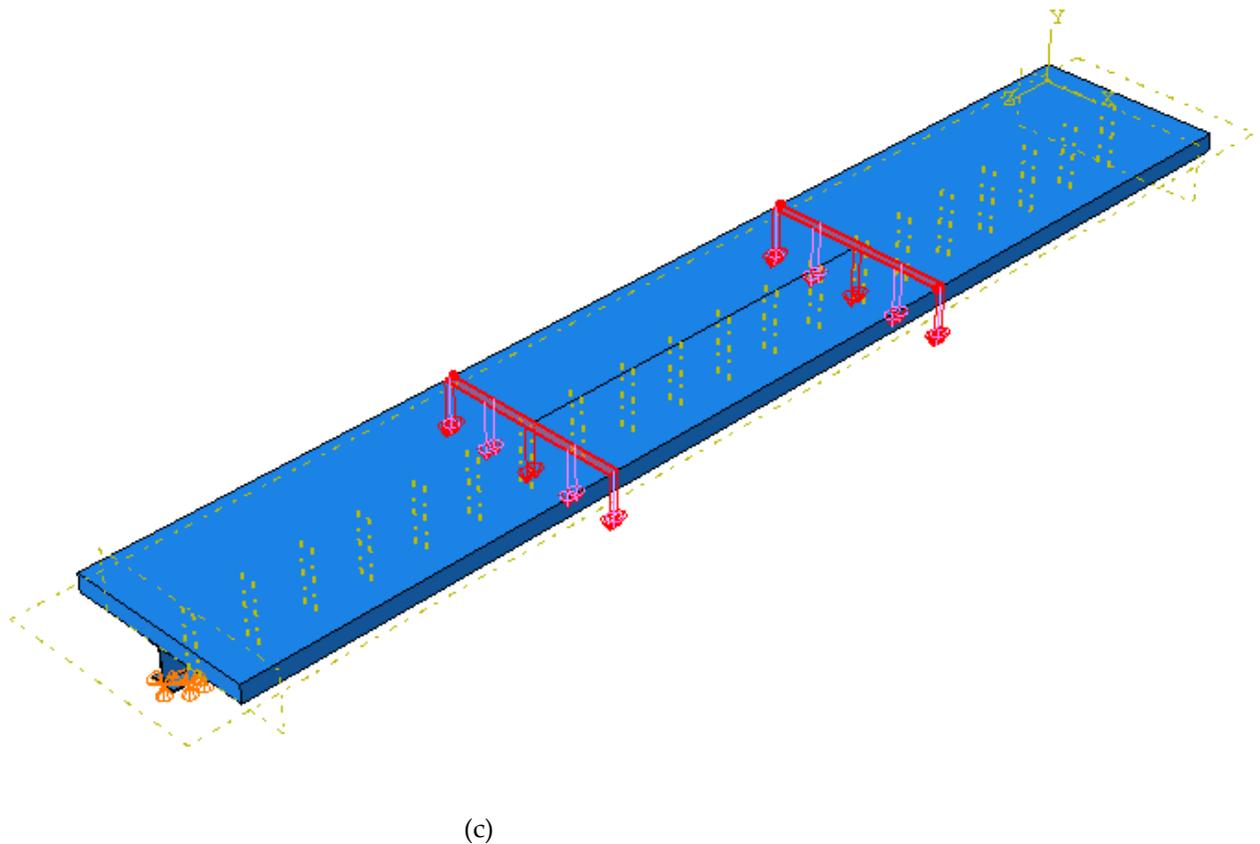


Figure 3 Boundary conditions (a) front view, (b) 3D view.

### 2.5 Mesh Discretization and Solution Strategy

The finite element model is discretized using a combination of hexahedral and tetrahedral elements to capture the geometry of the slab, girder, reinforcement, and connectors accurately. Mesh refinement is applied locally around shear connectors and rebar intersections to ensure precise stress prediction, while coarser mesh is used in less critical regions to reduce computational cost. Different mesh sizes are employed in a parametric manner to verify convergence of the results. The analysis is performed using nonlinear, displacement-controlled static analysis, accounting for material and geometric nonlinearity. Contact and tie constraints are defined to simulate interaction between the concrete slab, steel girder, and connectors, ensuring proper load transfer and composite action throughout the system. The following fig 4. represents the mesh of the model.

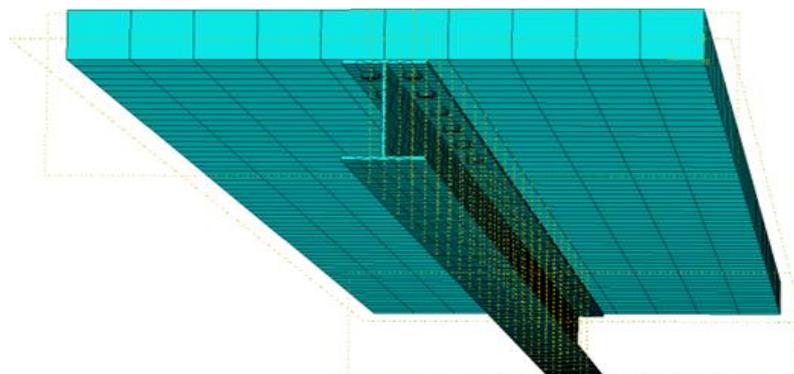


Figure 4 Mesh of whole Assembly.

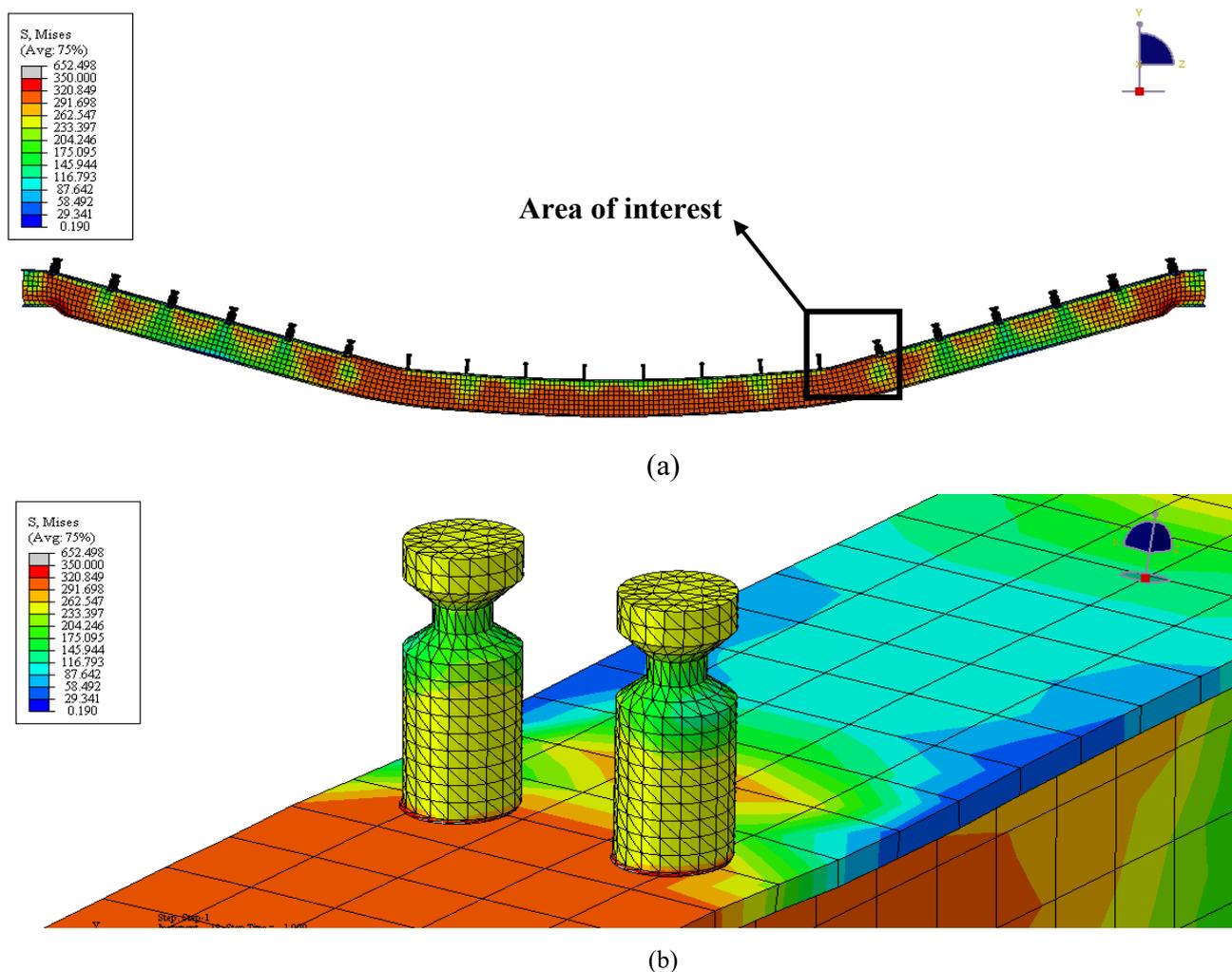
### 2.6 Parametric Study

A systematic parametric analysis is conducted to investigate the effect of connector material strength on stress distribution and composite behavior. Five different strength cases 400 MPa, 860 MPa, 900 MPa, 1250 MPa, and 1400 MPa are considered while keeping the geometry, connector spacing, boundary conditions, and displacement loading constant. This approach isolates the influence of connector stiffness and strength on local stress attraction and global load transfer. For each case, the finite element model is analyzed to evaluate peak stresses in headed studs and bolted connectors, as well as the overall deformation of the slab-girder system. The results provide insight into how increasing connector strength and stiffness affects interface force redistribution and identifies potential stress concentration zones.

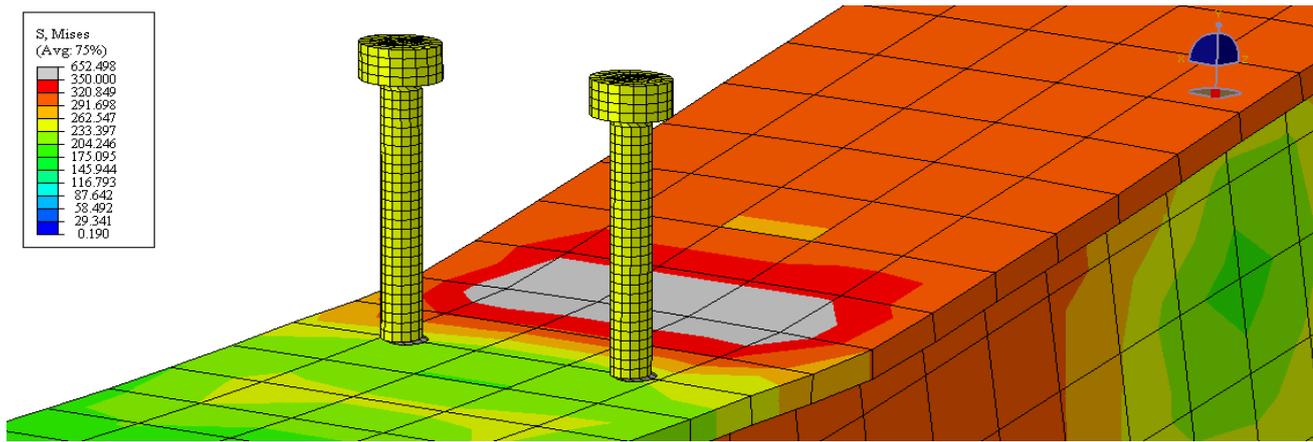
### 3. Results

#### 3.1 Stress Response for 400 MPa Strength

At a material strength of 400 MPa, the composite beam exhibits pronounced stress concentration in the steel girder, particularly near the mid-span and at the steel-concrete interface. The stress contours indicate early yielding in the steel section under the imposed displacement of 100 mm, accompanied by elevated stresses around the shear connectors. The overall stress distribution for this case is shown in Fig. 5.



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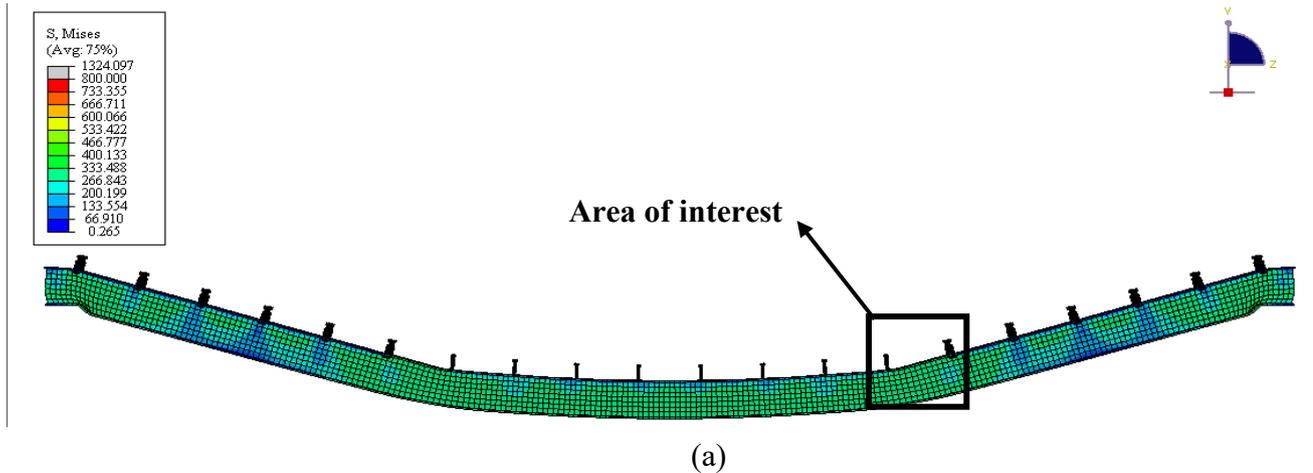


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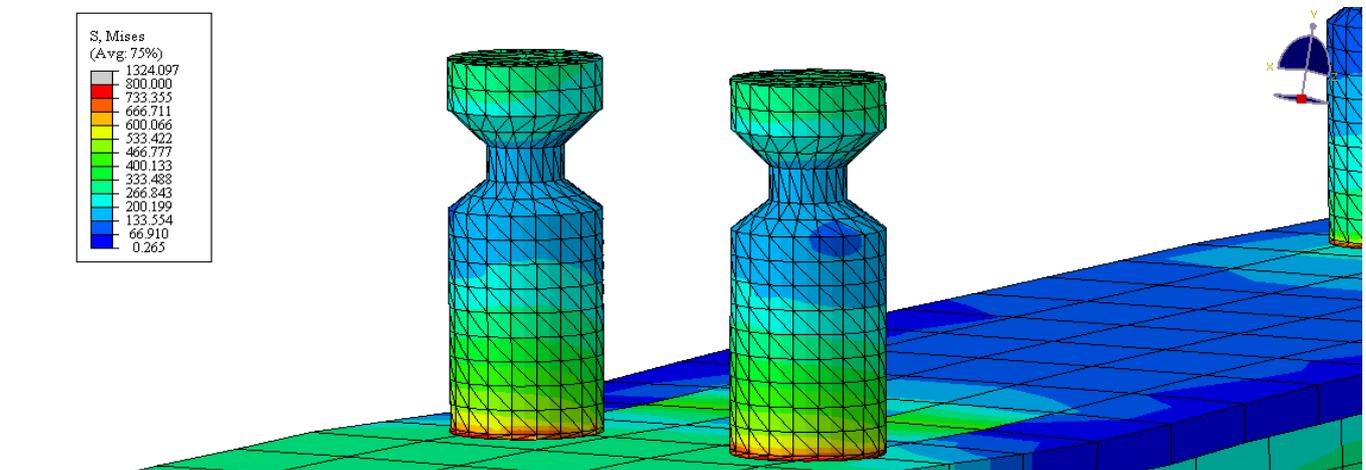
Figure 5 Stress distribution for 400 MPa, (a) side view, (b) removable bolts, (c) head studs.

### 3.2 Stress Response for 860 MPa Strength

For the 860 MPa strength level, a noticeable reduction in stress magnitude is observed compared to the 400 MPa case. Stress concentration at the steel–concrete interface is reduced, and yielding is confined to localized regions near the loading zone. The stress contours demonstrate improved stress redistribution within the steel girder, as illustrated in fig 6.



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(b)

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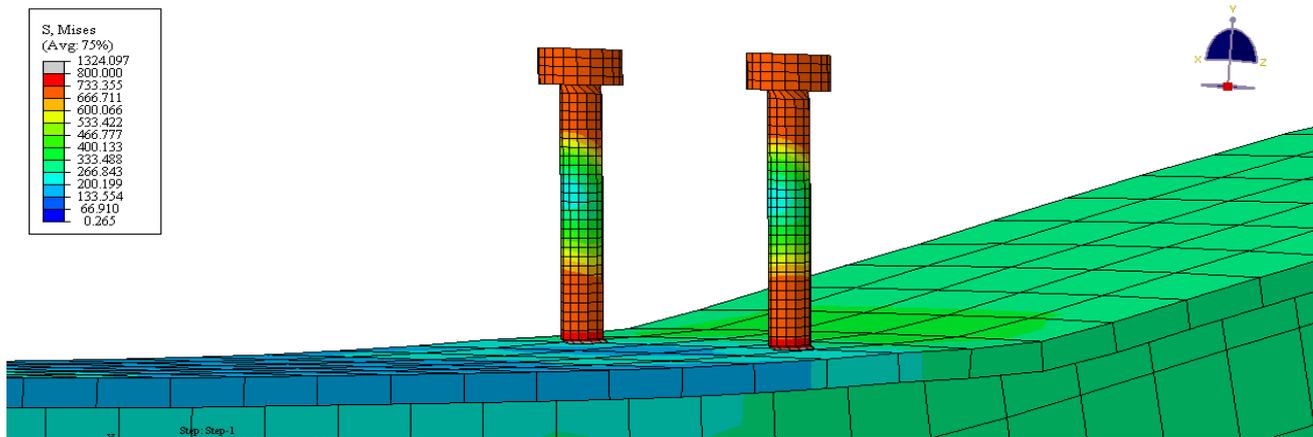
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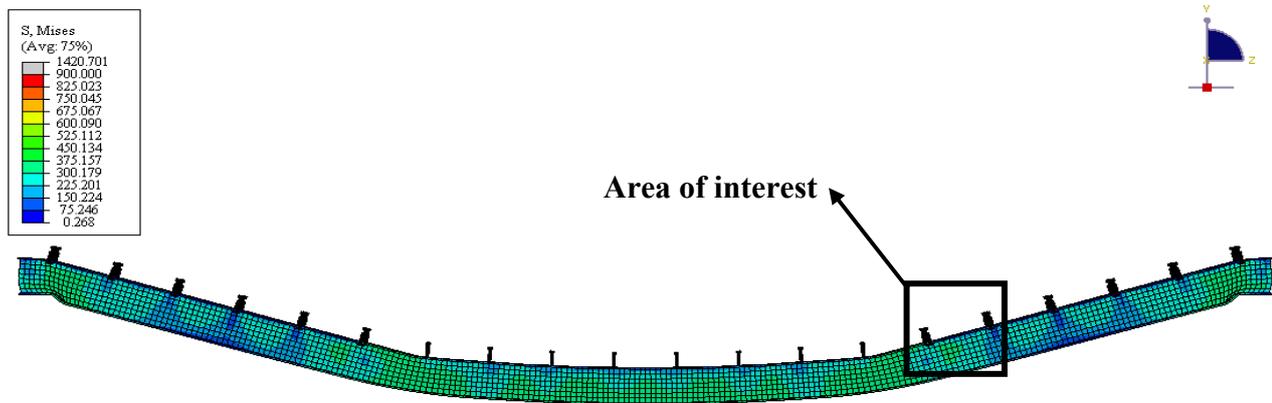


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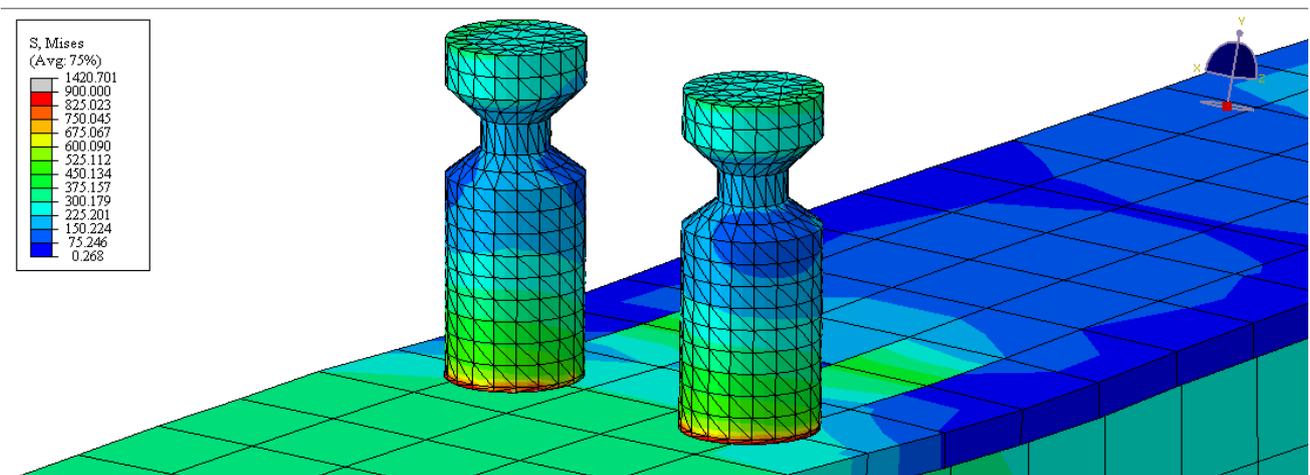
Figure 6 Stress distribution for 860 MPa, (a) side view, (b) removable bolts, (c) head studs

### 3.3 Stress Response for 900 MPa Strength

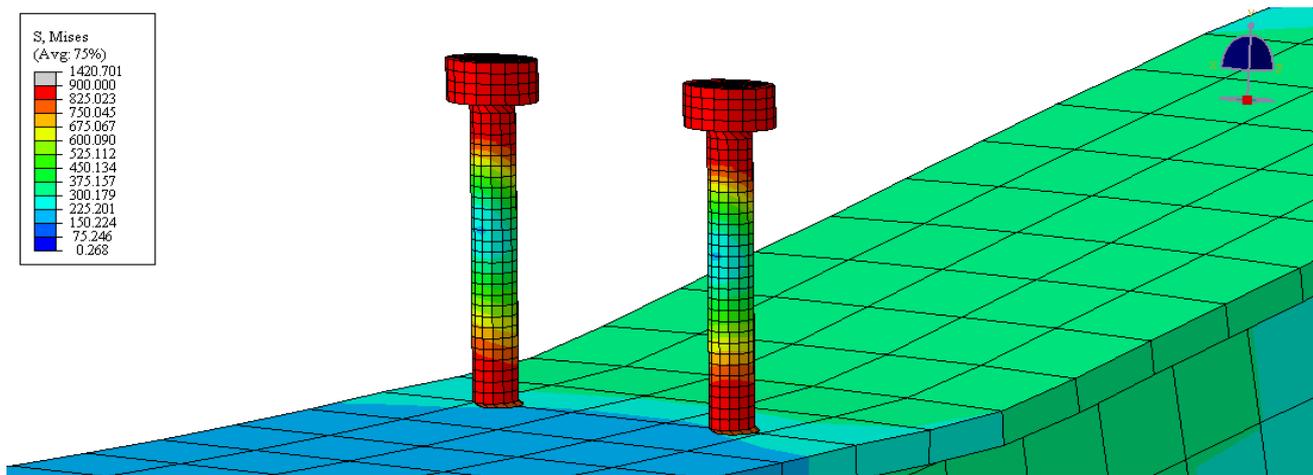
When the material strength is increased to 900 MPa, the composite beam shows further improvement in stress distribution. The steel girder remains predominantly within the elastic range, with limited high-stress regions near the shear connectors. The concrete slab experiences lower stress demand, indicating enhanced composite efficiency under the same displacement level. The stress pattern for this case is presented in fig 7.



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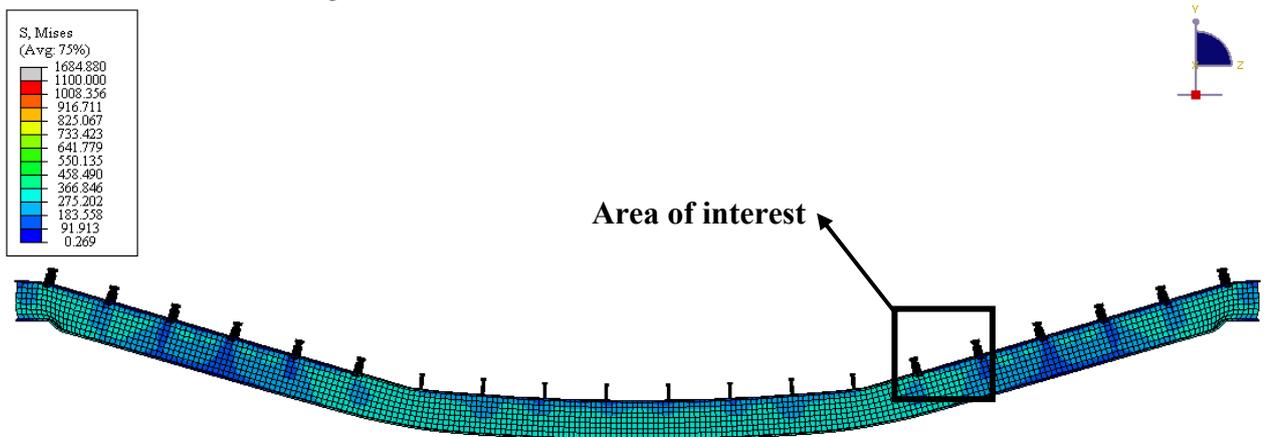


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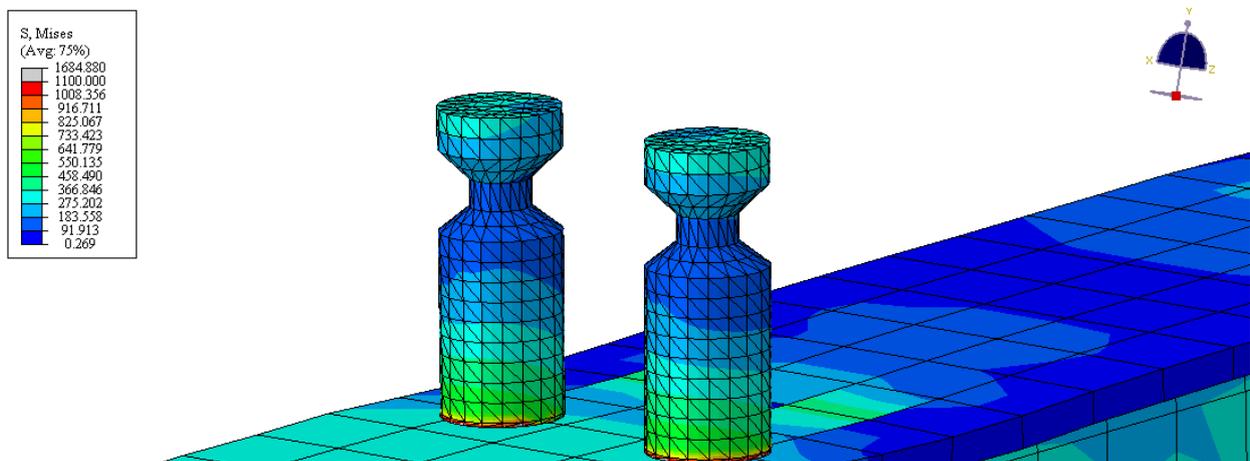
Figure 7 Stress distribution for 900 MPa, (a) side view, (b) removable bolts, (c) head studs

### 3.4 Stress Response for 1250 MPa Strength

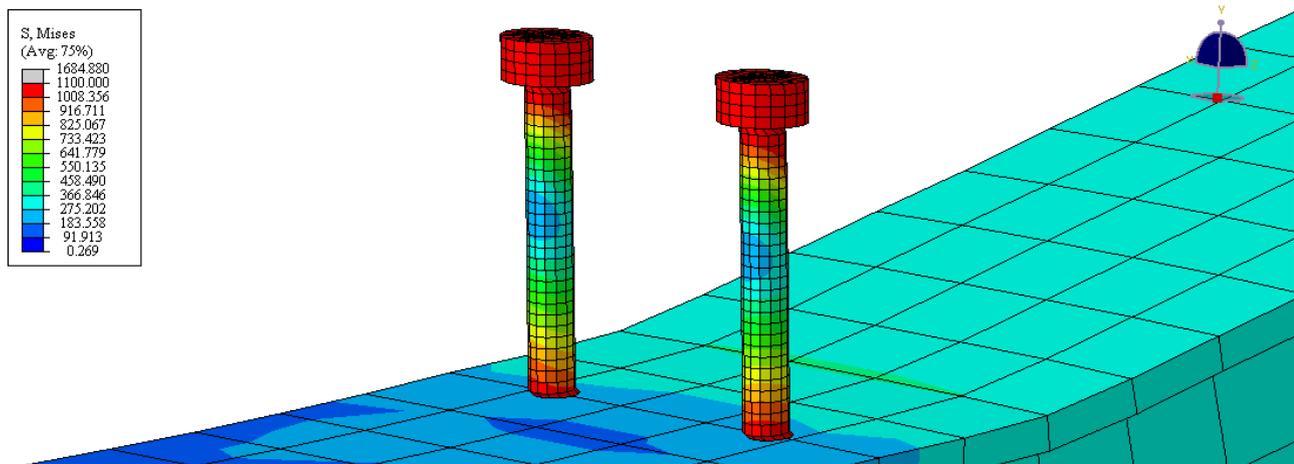
At a strength level of 1250 MPa, stress concentrations in the steel girder are significantly reduced, and the stress contours become more uniformly distributed along the beam length. Localized stresses near the connectors are minimal, reflecting effective load transfer and delayed nonlinear behavior. The corresponding stress contours are shown in fig 8.



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(b)

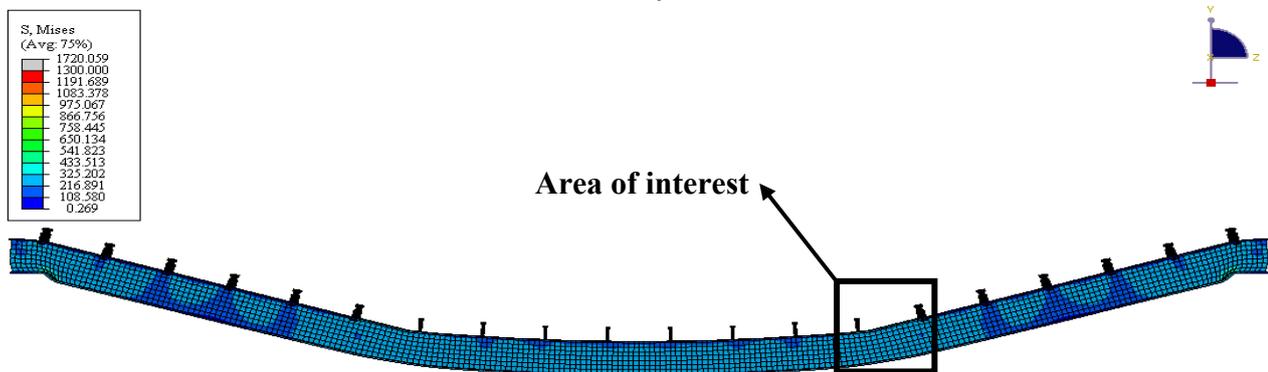


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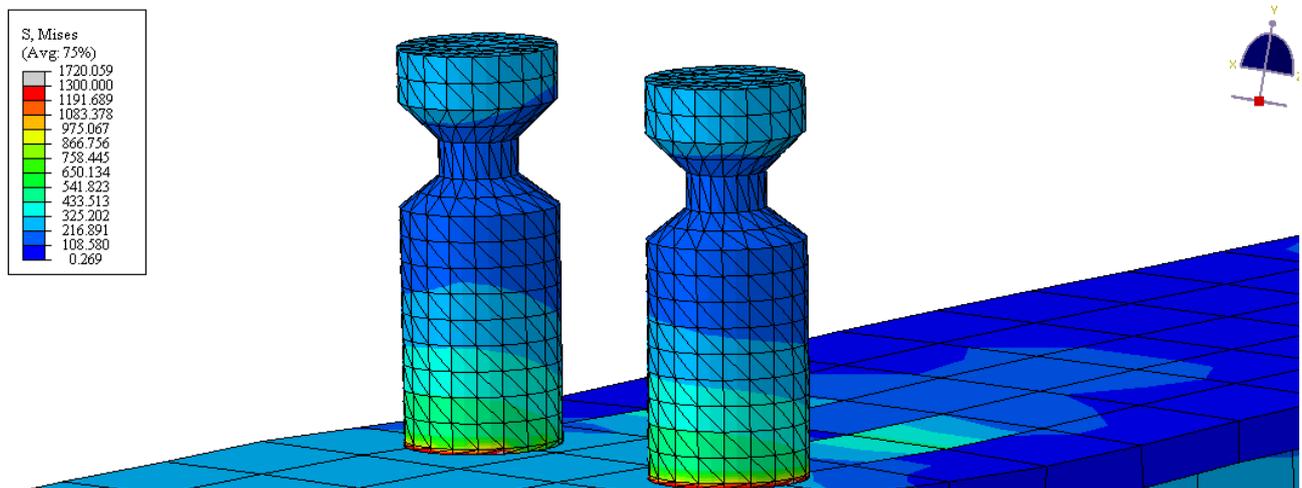
Figure 8 Stress distribution for 1250 MPa, (a) side view, (b) removable bolts, (c) head studs.

### 3.5 Stress Response for 1400 MPa Strength

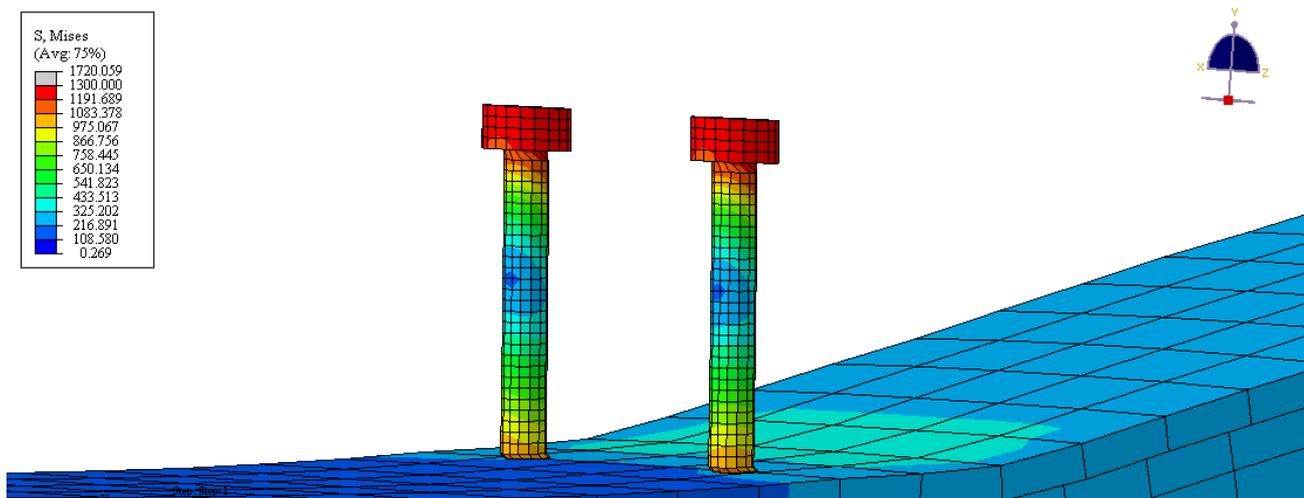
For the highest investigated strength of 1400 MPa, the composite beam demonstrates the most uniform stress distribution under the imposed displacement of 100 mm. The steel girder and shear connectors exhibit low stress demand, with no significant concentration zones observed. This behavior indicates superior resistance to large deformation and enhanced structural efficiency. The stress contours for this case are illustrated in fig 9.



(a)



(b)



(c)

Figure 9 Stress distribution for 1400 MPa, (a) side view, (b) removable bolts, (c) head studs.

### 3.5 Comparative Stress Trend

A comparative assessment of stress response for all investigated material strength levels under an identical displacement of 100 mm is summarized in Table 2. The comparison highlights the reduction in stress demand and stress concentration with increasing material strength. Lower strength cases exhibit higher peak stresses and pronounced localization, while higher strength cases demonstrate more uniform stress distribution and improved composite efficiency.

Table 2 Comparative Stress Trends

Material Strength (MPa)	Peak Stress in Steel Girder	Stress at Steel–Concrete Interface	Stress in Shear Connectors	Overall Stress Distribution
400	Very High	High	High	Highly localized
860	High	Moderate	Moderate	Localized
900	Moderate	Moderate	Low	Improved
1250	Low	Low	Very Low	Uniform
1400	Very Low	Very Low	Minimal	Highly uniform

## 5. Conclusions

The present finite element investigation of a composite slab–girder system demonstrates that shear connector material properties exert a decisive influence on both global deformation and local stress response. A parametric study was performed by varying the connector ultimate strength from 400 MPa to 1400 MPa, where the alternative strength levels were defined based on recognized material standards. Headed stud mechanical properties were adopted from ASTM A193/A193M (Table 2), mild steel properties from ASTM A36/A36M (Table 2), and high-strength alloy steel properties from EN 10083-3 (Table 3) for 42CrMo4 steel in the quenched and tempered condition. The numerical results indicate that high-strength connectors exhibit greater stiffness and reduced deformation, which leads to increased stress attraction and localized stress concentrations within the composite slab–girder assembly. In contrast, lower-strength connectors undergo larger

deformations, enabling improved force redistribution and a more uniform stress field at the steel–concrete interface.

From a design perspective, although high-strength connectors enhance composite action and effectively limit global deflections, their elevated stiffness may adversely affect fatigue performance and serviceability due to localized stress concentrations. Therefore, connector selection should not be governed solely by ultimate strength but must also consider stiffness compatibility, ductility, and deformation capacity. While higher-grade connectors are technically available, their consistent availability in local markets is not always guaranteed, which may restrict their practical application. Consequently, the use of moderately strong and ductile connectors that are readily available locally is recommended to achieve a balanced combination of structural efficiency, constructability, and durability. Finally, it is emphasized that experimental validation through full-scale or laboratory testing is essential to confirm the numerical findings and to finalize the design recommendations derived from this study.

#### **Conflict of Interest Statement**

The authors declare no conflict of interest.

#### **Author Contribution Statement**

Abdullah Ajeel: Model development, Parametric study, analysis.

Eisa Khan: literature review, validation, results interpretation.

Hafiz Ahmed Waqas: Conceptual guidance, technical review, and Supervision.

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#### **Data Availability Statement**

The data supporting the findings of this study are available from the authors upon reasonable request.

#### **Authors' Agreement Statement**

All authors have read the manuscript and agree on the submitted and published version.

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