WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2026.1370

ARCHIVES OF CIVIL ENGINEERING

Vol. LXXII ISSUE 3 2026

 pp. 109 –122

Research paper

Finite element analysis of steel-concrete composite beams with web openings

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Abstract: This study investigates the finite element analysis of steel–concrete composite beams with web openings using ATENA Science. Ten beams were modeled and analyzed, with nine containing web openings and one serving as a reference beam without openings. All specimens were fully shear-connected via shear studs. The main parameters studied include concrete flange thickness, reinforcement ratio, and opening height and length. Results indicate that web openings significantly reduce both load-bearing capacity and ultimate stiffness. The concrete slab above the opening carries most of the shear force across the section, contributing considerably to the section's shear capacity. Increasing the concrete flange thickness enhances load-bearing ability, while a higher reinforcement ratio improves deformation capacity. Wider openings substantially increase slip at the interface above the holes, and increasing the height of the openings results in greater shear load transfer to the concrete flange. It was observed that the CB4 concrete slabs carried between 60% and 69% of the total shear force; CB8 resisted about 60%, while CB10 showed a 54% increase in bearing capacity.

Keywords: composite beam, finite element analysis, interface slip, shear bearing capacity, web opening

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1. Introduction

In modern structural engineering, steel-concrete composite beams are vital, combining steel's tensile strength with concrete's compressive capacity. These composite beams integrate steel's tensile strength with concrete slabs' compressive strength through shear connectors, leveraging the strengths of both materials. This leads to members with enhanced load-bearing capacity, stiffness, and ductility. Thanks to their efficiency and cost advantages – including improved bearing capacity, stiffness, seismic performance, fire resistance, and durability [1–3] – such systems are widely used in modern construction. They are especially common in long-span and high-rise buildings to reduce height and costs [4–7].

An opening in an RC beam reduces its load capacity but results in higher service load deflections and cracks [8]. As building systems advance and the need for integrated Mechanical, Electrical, and Plumbing (MEP) systems grows, it becomes more important to integrate various pipelines such as water supply, drainage, gas, air conditioning, electrical conduits, and communication networks within structural components.

Various studies have explored the behavior of composite beams with web openings. Clawson and Darwin (1982) [9] conducted experimental tests on composite beams with rectangular web openings, demonstrating that the size and position of these openings significantly influence structural performance. Their findings stress the importance of considering these factors during design to prevent adverse effects on strength and ductility. Likewise, Ellobody *et al.* [10] used finite element analysis to examine composite beams with both stiffened and unstiffened web openings. Results indicated that beams with horizontal stiffeners exhibited a notably higher load-carrying capacity compared to those with unstiffened openings. Chung *et al.* [11] conducted an analytical study on non-composite cellular beams, emphasizing the Vierendeel mechanism around web openings. Table 1 summarizes the research on composite beams with web openings formed by solid slabs.

Hao Du *et al.* [12] investigated how reinforcement affects the web- opening strength of steel-concrete composite beams and found that longitudinal stiffeners significantly increase the maximum load capacity. This study aims to fill that gap through nonlinear finite element analysis, focusing on the effects of concrete flange thickness, reinforcement ratios, and opening sizes on structural behavior.

Table 1. Studies of composite beams with web openings created by solid slabs

Model	Reference	Highlight
Experimental	K.F. Chung *et al.* [13]	Steel and composite beams with large rectangular web openings based on plastic design methods.
	Granade *et al.* [14]	Investigated the stresses based on the Vierendeel mechanism
	Clawson and Darwin *et al.* [9]	Observed the influence of the slab on shear strength
	Cho *et al.* [15]	Sustained the slab's contribution to shear strength
	Narayanan *et al.* [16]	Observed the effectiveness of the headed stud on the steel-concrete interface

Continued on next page

Table 1 – *Continued from previous page*

Model	Reference	Highlight
Experimental	Roberts and Al-Amery *et al.* [17]	Investigated the effectiveness of bolted tension connectors on the steel-concrete interface
	Shanmugam *et al.* [5]	Conducted tests on steel-concrete composite girders featuring rectangular and circular web openings
	Chen *et al.* [6]	Conducted tests to verify the performance of composite cantilever beams with web openings
	Li *et al.* [18]	Performed tests on continuous steel-concrete composite beams with web openings
	M.A. Gizejowski and Kalil *et al.* [19]	Observed the behavior of composite cellular beams subjected to hogging moments
Analytical	Todd and Cooper *et al.* [20]	Neglected the slab's contribution to shear strength
	Donoghue *et al.* [21]	Suggested using reinforcements to increase shear strength
	Clawson and Darwin *et al.* [22]	Considered the slab's contribution to shear strength
Numerical	K F. Chung *et al.* [13]	Steel and composite beams with large rectangular web openings are designed using plastic methods.
	Bernice V.Y. *et al.* [23]	The effect of tensile membrane action on fire-exposed composite concrete floor-steel beams with web-openings
	Chen *et al.* [6]	Performed a non-linear analysis to examine the impact of opening size, stiffening plates, and the moment-shear ratio
	Li *et al.* [18]	Conducted geometrical nonlinear analyses to examine the effect of slab thickness and reinforcement rate
	Marian A. Gizejowski *et al.* [19]	Investigations on the distortional stability and ductility behavior of steel-concrete composite beams subjected to hogging bending
	N. Gattesco *et al.* [24]	Analytical modeling of the nonlinear behavior of composite beams with deformable connections
	Y.L. Pi *et al.* [25]	A total Lagrangian FE model was developed for the second-order nonlinear inelastic analysis of steel-concrete composite members.
	E. Ellobody *et al.* [26]	Finite element models for analyzing solid slabs, precast hollow core slabs, and composite girders

2. Properties and specimen details

In total, 10 specimens labeled CB1-CB10 were modeled; CB1, the control specimen, had no openings. The other nine beams featured different opening configurations. The study focused on variables such as the thickness of the concrete flange plate, the reinforcement ratio, and the opening sizes. All specimens were designed to ensure full shear connection. Figures 1 and 2 show the geometric details. The flange concrete was grade C40, the steel beams were Q235B I-sections, and the shear connectors were 19 mm in diameter and 80 mm long, spaced every 100 mm along the beam, following [27]. Table 2 summarizes the main parameters for each specimen.

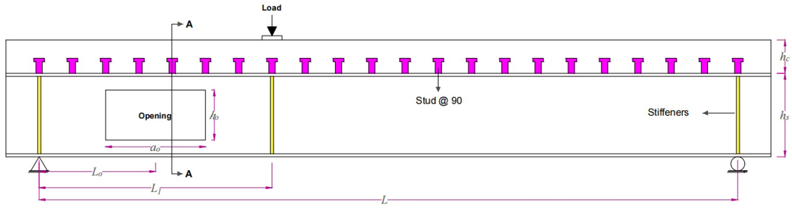

Fig. 1. Geometrical sizes of the specimen

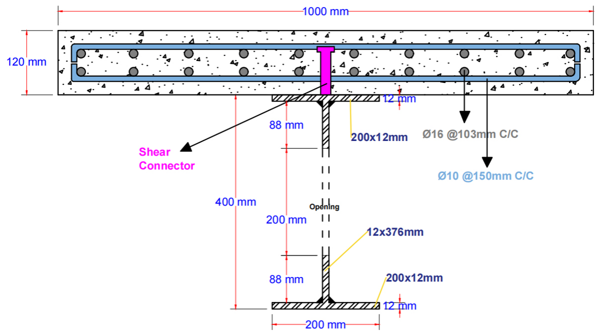

Fig. 2. Detailed cross-section of the specimen

Table 2. Details of the composite beam specimens

Specimen number	Opening size	Concrete slab		Reinforcement ratio (%)		Studs ϕ 19 vertically in a row	Steel beam	Clear span	Support to center of opening	Applied load location
	$a_0 \times h_0$ / mm	h_c	b_e	Hori	Veri		$(h_s \times b_f \times t_w \times t_f)$	L / mm	L_0 / mm	L_1 / mm
CB1	No opening	100	600	0.5	0.5	@100	250×125×6×9	2000	350	700
CB2	300 × 150	100	600	0.5	0.5	@100	250×125×6×9	2000	350	700
CB3	300 × 150	115	600	0.5	0.5	@100	250×125×6×9	2000	350	700
CB4	300 × 150	130	600	0.5	0.5	@100	250×125×6×9	2000	350	700
CB5	300 × 150	100	600	1.0	0.5	@100	250×125×6×9	2000	350	700
CB6	300 × 150	100	600	1.5	0.5	@100	250×125×6×9	2000	350	700
CB7	300 × 100	100	600	0.5	0.5	@100	250×125×6×9	2000	350	700
CB8	300 × 50	100	600	0.5	0.5	@100	250×125×6×9	2000	350	700
CB9	200 × 150	100	600	0.5	0.5	@100	250×125×6×9	2000	350	700
CB10	100 × 150	100	600	0.5	0.5	@100	250×125×6×9	2000	350	700

3. Finite-element analysis model

A three-dimensional nonlinear finite-element model was created using ATENA Science [28] to simulate the combined steel-concrete behavior in composite beams with web openings. This model employs different element types for concrete, reinforcement, steel profiles, and shear connectors, each chosen to model cracking, yielding, and interface slip accurately.

3.1. Material models

3.1.1. Concrete damage model

Figure 3 shows that the concrete behavior is modeled by the "Fracture-plastic model (3D Nonlinear Cementitious 2)" model in ATENA, which employs a smeared crack approach and a Menetrey-Wilam failure surface to capture tension cracking and compression crushing. The uniaxial compressive response follows a parabolic-linear curve, with a peak stress $f_c = 19.1$ MPa at strain $\varepsilon_0 = 0.002$, ultimate strain $\varepsilon_u = 0.0038$, and an initial modulus $E_c = 3.25 \times 10^4$ MPa. Tensile cracking is governed by fracture energy parameters consistent with Hognestad's Eq. (3.1).

$$\sigma = \begin{cases} f_c \left[2\frac{\varepsilon}{\varepsilon_0} - \left(\frac{\varepsilon}{\varepsilon_0}\right)^2 \right], & \varepsilon \le \varepsilon_0 \\ f_c \left[1 - 0.15\frac{\varepsilon - \varepsilon_0}{\varepsilon_u - \varepsilon_0} \right], & \varepsilon_0 \le \varepsilon \le \varepsilon_u \end{cases} \tag{3.1}$$

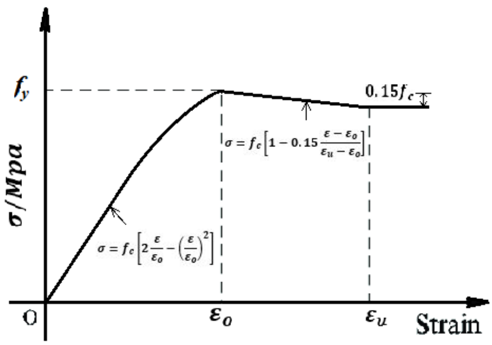

Fig. 3. Stress-strain curve of concrete

3.1.2. Steel constitutive law

All steel components, including the beam profiles, reinforcing bars, and any stiffening plates, adhere to a bilinear isotropic hardening law with the von Mises yield criterion. The stress-strain curve exhibits an ideal elastic-perfectly-plastic shape (see Fig. 4) with: the yield strength f_y of steel is 235 MPa; the elastic modulus E_s is 2.06×10^5 MPa; Poisson's ratio is 0.3, as indicated in Eq. (3.2).

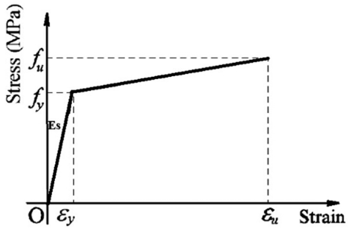

Fig. 4. Stress-strain model of steel

$$\sigma = \begin{cases} E_s\varepsilon, & \varepsilon < \varepsilon_y \\ f_y, & \varepsilon \geq \varepsilon_y \end{cases} \tag{3.2}$$

3.1.3. Shear-connector load-slip curve

The shear connectors are modeled in ATENA using zero-volume spring elements, with the empirical load-slip relationship from Ollgaard *et al.* [29] derived from push-out tests. The three-directional behavior is represented by orthogonal springs with distinct load-slip curves ($P - s$) in the longitudinal (x), transverse (y), and vertical (z) directions, as shown in Eq. (3.3) and Eq. (3.4). The main factors influencing the resistance capacity of the connectors are the connector diameter, the concrete slab thickness, the connection length of the concrete slabs, and the quantity and placement of the transverse reinforcement. Figure 5 shows the typical behavior of the head stud.

$$\begin{cases} P_x = N_v^c \left(1 - e^{-0.71 s_x}\right)^{0.4} \\ P_y = \dfrac{E_s A_{sd}}{L_s} s_y \\ P_z = N_v^c \left(1 - e^{-0.71 s_z}\right)^{0.4} \end{cases} \tag{3.3}$$

$$N_v^c = 0.43 A_{sd} \sqrt{E_c f_c} \leq 0.7 A_{sd} \gamma f \tag{3.4}$$

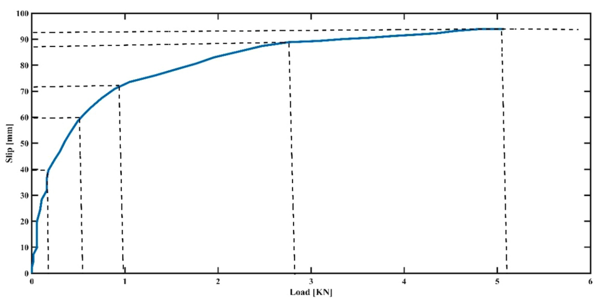

Fig. 5. Load-slip curve for shear connectors

In the formula: s_x, s_y, s_z is the relative slip amount in the x, y, z directions respectively; L_s is the length of the bolt; A_{sd} is the cross-sectional area of the shear connector; N_v^c is the shear bearing capacity of a single bolt; f is bolt tensile strength; γ is the material strength ratio.

3.2. Finite element models

Mesh refinement was applied locally around openings to capture high stress gradients without excessively increasing the global element count. Rigid bearing plates (stiffeners) were placed at load and support points to prevent local convergence issues, as shown in Fig. 6. The analysis employed force-controlled loading, a displacement-based convergence criterion, von Mises yield checks for steel, and the Newton–Raphson nonlinear solver in ATENA.

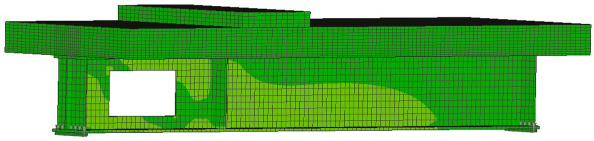

Fig. 6. A typical finite element model used in simulation

4. Analysis of computational results

4.1. Parametric study

4.1.1. Influence of slab thickness

The effect of different concrete slab thicknesses of 100 mm, 115 mm, and 130 mm, while keeping reinforcement ratios and hole dimensions constant. Specifically, specimen CB2 showed a 47% decrease in bearing capacity and a 42.5% reduction in deformation capacity compared to the solid-web specimen CB1. However, increasing the slab thickness in specimens CB3 and CB4 led to considerable performance improvements compared to CB2, with increases in bearing capacity of 11.5% and 26%, respectively. This improvement is due to the increased shear resistance from the thicker concrete slabs, although the deformation capacity remained essentially unchanged, shown in Fig. 7. The result revealed that the concrete slabs CB3 and CB4 carried between 60% and 69% of the total shear force, with the steel beam above the opening bearing 24% to 18%, and the steel beam below bearing 16% to 12%.

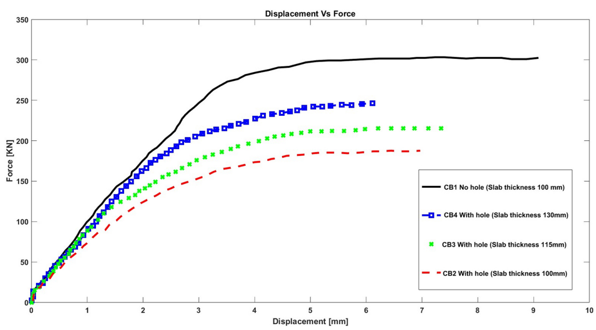

Fig. 7. Effect of concrete slab thickness

4.1.2. Effects of reinforcement ratio

The effects of reinforcement ratios at 0.5%, 1.0%, and 1.5% were examined while maintaining constant slab thickness and hole dimensions. As shown in Fig. 8, specimens CB5 and CB6 experienced modest increases in bearing capacity by 6% and 11.5%, respectively, compared to specimen CB2. However, their deformation capacities increased more notably, with gains of 27% and 34.6%. These findings indicate that while higher reinforcement ratios slightly boost load-bearing capacity, they significantly enhance the deformation capacity of composite beams with web openings.

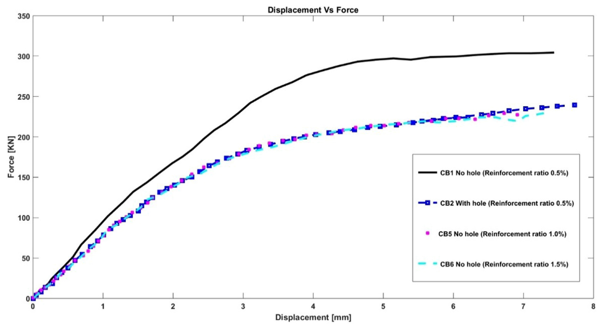

Fig. 8. Influence of concrete slab reinforcement ratio

4.1.3. Effects of opening width

The impact of opening widths of 100 mm, 200 mm, and 300 mm was studied, while keeping the reinforcement ratio, slab thickness, and opening height constant. Figure 9 shows that decreasing the opening width significantly improves both bearing and deformation capacities. Specimens CB9 and CB10 exhibited increases in bearing capacity by 17% and 54%, respectively, and in deformation capacity by 36% and 45%, respectively, compared to specimen CB2. This suggests that narrower openings boost structural performance by 8% (from 60% to 52%), with corresponding increases in the steel beam's contribution.

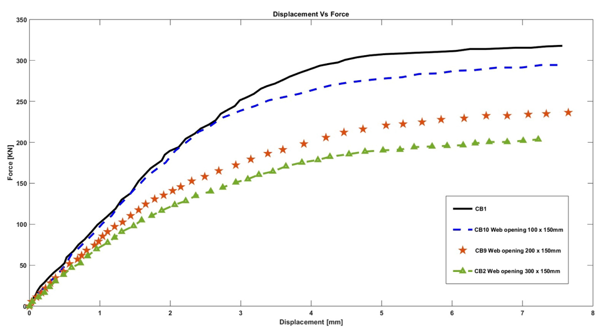

Fig. 9. Comparison of the specimen's opening width

4.1.4. Effects of opening height

The height of openings in steel-concrete beams impacts their performance, especially shear capacity and stability, as shown in Fig. 10. Specimens CB7 and CB8 showed that reducing the opening height increased the slab's shear contribution from 41% to 60%, with steel beam contributions also increasing, highlighting how opening size affects shear distribution. Larger web openings can cause greater deflections and lower load capacity in composite beams. Studies indicate that larger openings reduce shear capacity and may shift the failure mode from ductile to brittle, especially in high shear areas, significantly impacting performance.

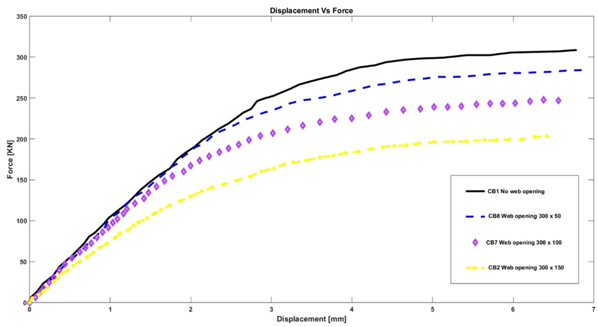

Fig. 10. Influence of opening height

4.2. Deformation analysis

This results in increased overall bending deformation and reduced shear stiffness. The upper and lower parts of the perforated segment have relatively low stiffness, resulting in deformation that resembles a hollow web truss, as shown in Fig. 11.

The current study assumes that the steel beam web supports the vertical shear in composite beams. However, when the web of a composite beam is perforated, the effective area of the steel beam web is significantly reduced, which diminishes the stiffness of the composite beam and consequently lowers the bending and shear capacity of the perforated section. Therefore, web-perforated composite beams may undergo three main failure modes:

1. **Shear failure:** When the section above the opening in a perforated composite beam does not have enough shear capacity, the concrete slab above will fail in shear before four plastic hinges form at the edges of the steel beam opening.
2. **Bending failure:** When the bending-to-shear ratio (M/V) at the section with the opening is relatively high, the section experiences a significant bending moment with a smaller shear force. During failure, the T-shaped steel section beneath the opening will yield first, followed by the concrete flange crushing, which will lead to bending failure.
3. **Vierendeel failure:** When the bending-to-shear ratio (M/V) is low or when the shear force at both ends of the opening is high, the bending moment in the web at the openings becomes significant for the overall performance of the beam. This results in a four-hinge Vierendeel mechanism failure (the most common failure), as shown in Fig. 11.

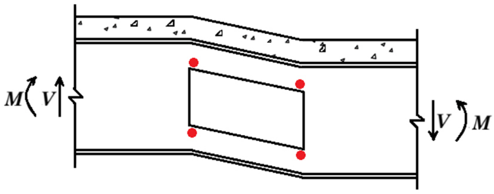

Fig. 11. Vierendeel deformation

4.2.1. Deflection analysis

Figure 12 displays the deflection profiles under various loading conditions. Specimen CB2, with a large web opening (300 × 150 mm), showed maximum deflection at the right end of the opening, indicating significant shear deformation in the opening area. Specimen CB8, with a smaller opening height (300 × 50 mm), exhibited the most excellent deflection between the right end of the opening and the point of load application. Specimen CB10, despite having a smaller opening width (100 × 150 mm), experienced maximum deflection at the load application point. These observations indicate that opening height significantly affects deflection behavior, with greater heights leading to greater shear deformation and a higher risk of failure. Results also revealed that decreasing the opening height reduced the slab's shear contribution from 60% to 41%. In contrast, the contributions from the steel beams increased, emphasizing the importance of opening dimensions on shear distribution.

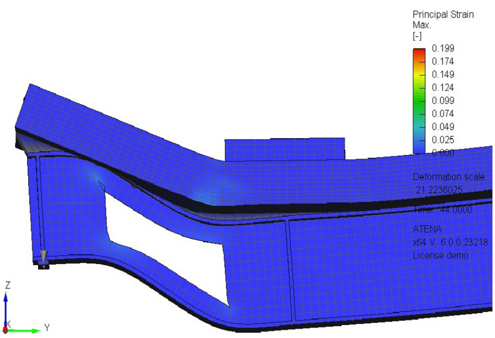

Fig. 12. Deflection of the specimen

4.2.2. Cracking in the concrete slab and deformation in the plate girder

Under applied loads, steel-concrete composite beams are susceptible to buckling-induced cracking, particularly in regions with structural discontinuities, such as web openings or material imperfections, as shown in Fig. 13. Studies indicate that cracks, particularly near critical regions such as the web or the flange, significantly reduce the buckling capacity of beams. Finite element analyses, such as those performed with ATENA Science, have effectively simulated these phenomena, offering insights into the complex interaction between buckling behavior and crack formation.

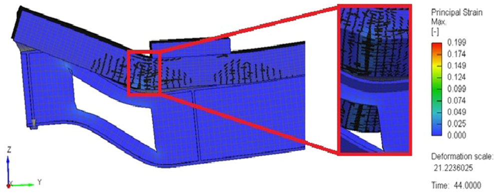

Fig. 13. Concrete slab crack failure in the composite beam

4.2.3. Slip analysis

The relative slip along the beam length under different loads is analyzed. Specimen CB1 showed minimal slip, with a gradual increase near the beam ends as the load approached $0.75P_u$ of the ultimate load, indicating the onset of plastic deformation in the bolts. Specimen CB2 experienced a sharp increase in slip in the opening area when the load reached about $0.5P_u$ of the ultimate load, with the left end of the opening exhibiting three times more slip than the right end under ultimate load. Specimen CB8 showed a similar trend, with the left end of the opening having 2.16 times more slip than the right end under ultimate load. Specimen CB10, with a narrower opening, maintained a more uniform slip distribution, indicating that opening width significantly influences slip behavior.

4.2.4. Shear connector crack

While shear connectors at the interface of composite beams are typically placed discretely, their spacing is often small and not aligned with the length of the beam elements. Consequently, it is essential to initially consider the shear connectors as continuous and then discretize them based on the length of the beam elements. This approach requires only a single spring element at each end of every composite beam segment, as illustrated in Fig. 14.

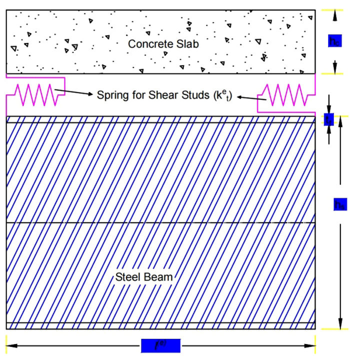

Fig. 14. An illustration of the spring element of the shear connector

The stiffness of a single spring is denoted as $k_T^{(e)}$ in Eq. (4.1).

$$k_T^{(e)} = \frac{kl^{(e)}}{2a} \tag{4.1}$$

where: k is the stiffness of an individual shear connector uniformly distributed along the beam; $l^{(e)}$ is the element length; a is the spacing of the uniformly distributed shear connectors in the beam element.

A standard failure mode involves cracks starting at the base of welded stud connectors, often due to stress concentrations and material imperfections, as shown in Fig. 15. These cracks can expand under cyclic loading, leading to brittle fractures with minor prior deformation and thus reducing the beam's load-carrying capacity. Additionally, the surrounding concrete can display cracking patterns, especially near the shear connectors. In some cases, concrete spalling has been observed near the connectors, indicating significant damage to the concrete component.

Finite element analyses, such as those performed with ATENA Science, accurately simulate cracking behavior, providing insights into the failure mechanisms of shear connectors and the entire composite beam system.

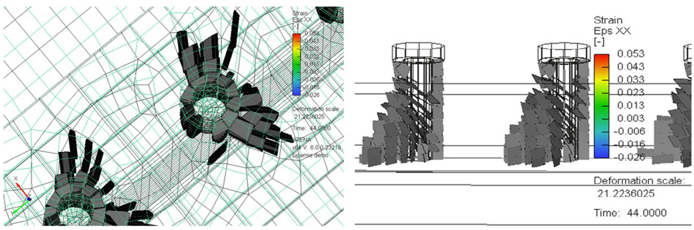

Fig. 15. Cracks propagation around the shear connector (Part 1)

These findings emphasize the critical role of the concrete slab in shear resistance for composite beams with web openings. However, current design codes [30,31] often overlook the slab's contribution, leading to underutilization of material strength and potential inefficiencies.

5. Conclusions

- Introducing web openings in steel-concrete composite beams significantly reduces their load-bearing capacity and stiffness. Moreover, these modifications negatively impact the beams' deformation ability.
- Finite element analyses using ATENA Science on nine composite beam specimens with web openings show that the concrete slab above the opening supports between 40% and 69% of the total sectional shear force. This highlights the concrete slab's important role in resisting vertical shear in beams with web openings.
- Increasing the thickness of the concrete slab effectively enhances the load-bearing capacity of composite beams with web openings. This improvement is due to the increased shear resistance of the thicker slab. However, this change does not significantly affect the beams' deformation capacity.
- Increasing the reinforcement ratio within the concrete slab results in modest improvements in both load-bearing capacity and stiffness of the composite beam, but the most significant benefit is seen in the increase of the beam's deformation capacity.

– An increase in the height of the web opening reduces the residual web area, which causes stress concentrations, especially at the corners of the opening. As the applied load approaches approximately $0.5P_u$, yielding begins in these concentrated areas, forming plastic regions. Consequently, internal forces are redistributed, with the concrete slab bearing a larger portion of the shear force, while the steel beam's contribution levels off.
– Widening the web opening significantly increases the relative slip at the interface within the opening area. Under maximum load conditions, the slip at the left end of the opening can be up to three times that at the right end, with the greatest slip occurring within the opening.

Acknowledgments

The authors extend their appreciation to the Faculty of Civil Engineering, Department of Structural Engineering, Akademicka 5, Joint Doctoral School, Silesian University of Technology, Akademicka 2A, Gliwice 44-100, Poland. The publication was supported by the Excellence Initiative – Research University program implemented at the Silesian University of Technology, year 2025–2026, grant number 32/014/SDU/10-21-14.

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Received: 2026-02-19, Revised: 2026-04-07