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Research Article

Finite Element Study on Cyclic Behavior of Composite Beam Subjected to Fully Reversed Cyclic Loading

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Abstract

Steel-concrete composites are frequently employed as the primary structural components of floors or as the primary carrying girders in bridge engineering. Due to limited research on composite structural steel sections, the effect of some parameters is not well documented on the current building codes. This thesis considered the effects of aspect ratio (ln/h), doubler plate thickness and different shear stud arrangements in a numerical research conducted using ABAQUS/Standard to investigate the performance of composite structural beam sections under cyclic loading. Experimental results from other researchers validated the accuracy of the numerical model. A total of ten specimens including a control specimen were simulated by varying the aspect ratio, doubler plate thickness and shear stud configuration of the composite structural beam sections. Finite-element analysis results showed that use of lower aspect ratio and higher doubler plate thickness improved the peak load carrying capacity by 97.71% and 60.72% respectively. Using cross arrangement of the shear stud showed better load carrying capacity compared to the horizontal and vertical arrangements. The stiffness and energy dissipation capacity of the composite beam improved by using lower span to depth ratio, higher doubler plate thickness and crossly arranged shear stud arrangements.

Keywords

Composite Steel, Stud Shear Connector, doubler plate thickness, Cyclic Loading, Composite Concrete Beam

1. Introduction

1.1. General

An experimental investigation of steel-concrete composite beams with different shear connections under fatigue and monotonic loads was conducted by Wang et al. [1]. They looked into how different shear connection strengths affected the fatigue and static performance of eight steel-concrete composite beams. First, a range of shear connection degrees was used to evaluate the steel-concrete composite beams' ultimate capacity, ductility coefficient, failure causes, strain distribution at the mid-span section, and relative slip distribution under monotonic loads. It was investigated how fatigue life, failure mechanism, and other mechanical parameters were affected by the degree of shear connection during fatigue loading. The findings reveal that the mechanical properties of the steel-concrete composite beams under monotonic and fatigue loads decrease as the shear connection degree increases. In multi-story steel frame buildings, the utilization of composite action between steel beams and concrete slabs is widely recognized as a more economical plat-

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form layout. Shear connectors (headed stud), which create a composite action between steel beams and concrete slabs, significantly increase the steel beams' stiffness, transferring longitudinal shear pressures at the steel-concrete interface and load-bearing capacity. When used in design, this action can lead to significant reductions in steel weight and construction depth. According to Mohammed, M. S., a finite element program can be used to create the detailed response of composite beams over the entire loading range up to failure. He also claimed that the failure in the analysis was not due to buckling or significant deformation, and he utilized a two-dimensional model to find a highly accurate prediction of the behavior of steel and concrete composite beams [2]. According to Liu, Y. and Glass, G. A., if the modal is constructed with the finest mesh coat, the analysis will be finished in less than 20 seconds. They also stated that the structural analysis requires the right mesh creation. Only regular shapes were modeled by him, but he claimed that irregular shapes could also be modeled. His research can be used to solve problems with heat transfer and fluid movement [3]. The tetrahedral element is more accurate than the hexahedral element, according to Liu, W., Geni, M., and Yu, L. When a structure has a surface boundary of higher order, the boundary can approach precisely. Changing the element size in modal analysis might increase calculation inaccuracy. Changing the mesh size to a single point or location stabilizes the calculation accuracy [4]. Model simplifications are crucial in simulation analysis. Occasionally, if there are more pieces or grids, the analysis will take longer to complete, which will lead to inaccurate results [5]. To examine the behavior of composite beams subjected to reverse loading, researchers in this field frequently use numerical simulations, experimental experiments, or a mix of both. The findings of these research can assist engineers and designers in creating better building methods and design standards to improve the performance and safety of composite structures under reverse loading circumstances. Numerous investigations on composite beams have been carried out by Lignos and his associates [6-8].

Using spring components to simplify the behavior of shear connectors is an alternate strategy. Parametric analysis is made possible by this method's significant reduction in calculation time. Sakai et al. [9] and El Jisr et al. [7] first used this strategy. Nevertheless, the impact of shear connection characteristics on the structural performance of composite beams has not yet been thoroughly investigated in these research.

The purpose of the study is to evaluate the structural integrity of composite beams by analyzing how they react to reverse loading circumstances. The study examines the behavior and structural performance of composite beams under situations of reverse loading. Reverse loading occurs due to unanticipated loading condition, change in structural configuration and in adequate design consideration. So, this numerical investigation is done for the occurrence of reverse loading of sample specimen to have equations to assess structural performance precisely considering various influential factors of composite structures. This study conducted a finite element analysis and revealed the result on the following parameters composite beam subjected to cyclic loading, span to depth ratio of the structural beam section, effect of shear stud configuration and doubler plate thickness on the structural beam.

1.2. Statement of the Problem

The behavior of composite beams under cyclic loading involves significant non-linearity restricting from multiple sources: concrete crushing and cracking, steel yielding and strain hardening, and, critically, the inelastic slip and damage accumulation within the shear connection interface. While conventional cyclic testing like incremental loading protocols can provides valuable data, the specific scenario of fully reversed cyclic loading. Where the beam is pushed symmetrically into both positive and negative plastic ranges is particularly disadvantageous and representative of severe earthquake response. Existing analytical and simplified Finite Element (FE) models struggle to accurately capture the cumulative damage and hysteretic response, especially related to the pinching effect and stiffness degradation caused by repeated shear connector failure and concrete gap opening/closing. A reliable, high-fidelity numerical model is currently lacking to accurately predict the load-displacement hysteretic curves, energy dissipation capacity, and ultimate failure modes of composite beams under these severe, fully reversed conditions. As a result, this thesis was aimed to examine the behavior of composite beam sections under the basic parameters such as aspect ratio (ln/h), shear stud configuration and doubler plate thickness.

1.3. General Objective

The main objective of this study was to investigate the composite steel beam behavior under cyclic loading using nonlinear finite element analysis.

1.4. Specific Objective

1) To analyze the behavior and performance of composite steel beam with different parameters under seismic loading.
2) To analyze the performance of composite steel beam considering the span to depth ratio of the structural steel beam sections.
3) To investigate the influence of the different shear stud configuration on failure mechanism and load displacement cyclic result of the composite beam sections.
4) To determine the optimal doubler plate thickness attached to the structural beam for seismic strengthening of composite beams.

1.5. Significance of the Study

This research signifies the importance of understanding how composite beams (steel and concrete) behave under repeated loading and unloading, a critical aspect for designing structures like bridges and buildings to withstand seismic activity or other cyclic forces. So this research work further contribute to researchers, designers, and academicians about the effect of span to depth ratio, shear stud configuration and doubler plate thickness under cyclic loading. It have the potential to significantly enhance the seismic performance of composite structures, provide practical retrofitting options, and add to the body of knowledge in the discipline of structural engineering.

2. Methodology

Conducted an experimental study on a component model of a composite beam to thoroughly evaluate its structural performance, considering various influential factors [10]. This specimen comprises two H-section steel headed studs welded to H-section steel beams, along with rebar and a concrete slab. It is symmetrical about the z-axis to specifically analyze pure shear behavior. The concrete was cast along the x-axis to reflect realistic construction practices. The assembly involved bolting the web using splice plates prior to testing. To prevent adhesion and friction during casting, the contact surface of the jig was coated with lubricating oil. The specimen was positioned widthwise on the footing beam, and external loading was applied via a horizontal jack capable of up to 1,000 kN. To constrain concrete slab warping, steel plates and H-section steel ties connected by steel bars were used.

The specimen diameter, length, width and strength are specified according to experimental investigation.

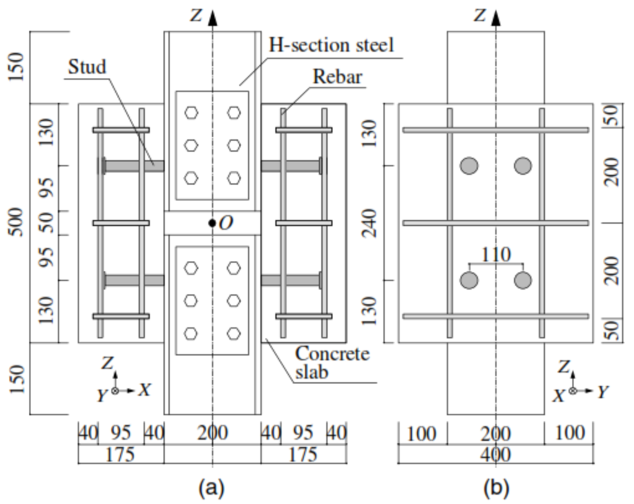

Figure 1. Component model for front and side view.

From the 14 specimens, 1 specimen selected with 7 experimental parameters:

1) Stud shank diameter - 22 mm
2) Stud height - 130 mm
3) Concrete slab width - 400 mm
4) Concrete strength - 29.1 N/mm^2
5) Pitch of rebar - 200 mm
6) Diameter of rebar - 10 mm, and
7) Loading protocol - fully reversed cyclic

The material properties are:

Table 1. Material properties of concrete.

W: C (%)	Compressive Strength (N/mm^2)	Tensile Strength (N/mm^2)	Modulus of elasticity (N/mm^2)
51	29.1	3.6	20,111

Table 2. Material properties of headed stud.

Diameter (mm)	Length (mm)	Yield Stress (N/mm^2)	Ultimate Stress (N/mm^2)	Elongation (%)
22	130	384	464	27

Table 3. Material properties of rebar.

Diameter (mm)	Yield Stress (N/mm^2)	Ultimate Stress (N/mm^2)	Elongation (%)
10	372	509	28

Table 4. Material properties of H section steel.

Parameter	Value
Yield Stress (N/mm^2)	291
Ultimate Stress (N/mm^2)	427
Elongation (%)	44

Nonlinear finite element analysis of the composite beam specimens, a series of analysis steps were defined within ABAQUS/Standard. To accurately solve the nonlinear equations, an appropriate solution algorithm specifically, the Newton-Raphson method is employed. During each load step, load increments are iteratively performed until convergence criteria are met, ensuring the structure reaches equilibrium. After each successful load increment, the stiffness matrix is updated to account for the changing structural stiffness caused by nonlinear material and geometric effects. This iterative process continues until all steps are complete. To enhance convergence efficiency, the analysis uses automatic small time steps and limits the maximum number of increments, facilitating a stable and accurate solution process [11, 12]. Significant advancements in nonlinear inelastic analysis techniques for ordinary and composite beams and framed structures have been made in recent years, and these techniques have been incorporated into increasingly sophisticated and logical analysis and design processes [13-16]. For example, accurate nonlinear analysis methods and procedures are needed to estimate inelastic limit states that approach and surpass the structural collapse. Extreme loads, such as those brought on by an earthquake or bomb, may cause the structure to surpass these limitations.

The analysis procedure includes the model of the specimens, including their geometry. Then, it details the input modeling strategies necessary for nonlinear FEA, such as selecting appropriate material constitutive models, element types, meshing procedures, boundary conditions, load application methods, and solution techniques for simulating under cyclic loading. A mesh sensitivity analysis and calibration of the concrete damaged plasticity (CDP) model parameters based on existing experimental data are also discussed.

3. Result

The study includes both model validation results and parametric investigations. Key parameters examined are the effect of span to depth ratio, shear stud configuration, and doubler plate thickness.

Load displacement response

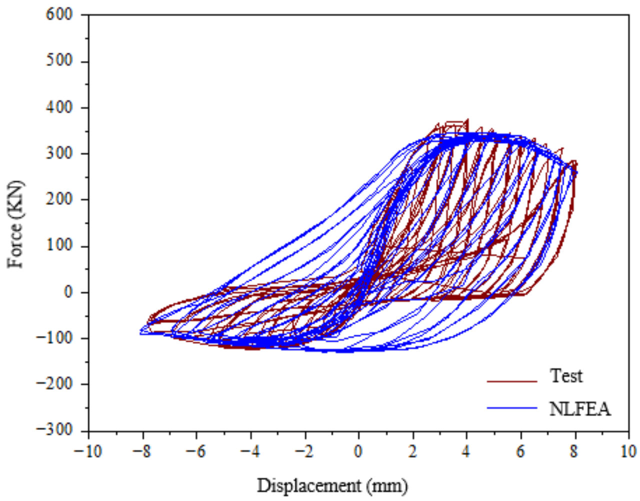

Figure 2. *Comparison of hysteretic curves.*

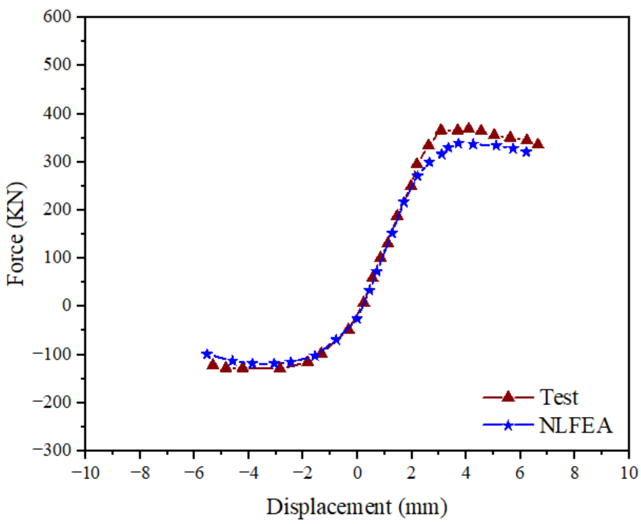

Figure 3. *Envelope curve comparison.*

Table 5. *Comparison of FEA and experimental tests based on maximum load capacity.*

Specimen	Loading direction	Δ(mm)				Average maximum load (KN)			
		Exp.	FEA	Error (%)	M (%)	Exp.	FEA	Error (%)	M (%)
Test (b)	Positive	7.92	8.34	5.31	94.96	380	365	3.94	96.05
	Negative	7.81	7.72	1.15	96.52	130	120	7.89	92.20

Result based on Composite Beam Span to Depth Ratio

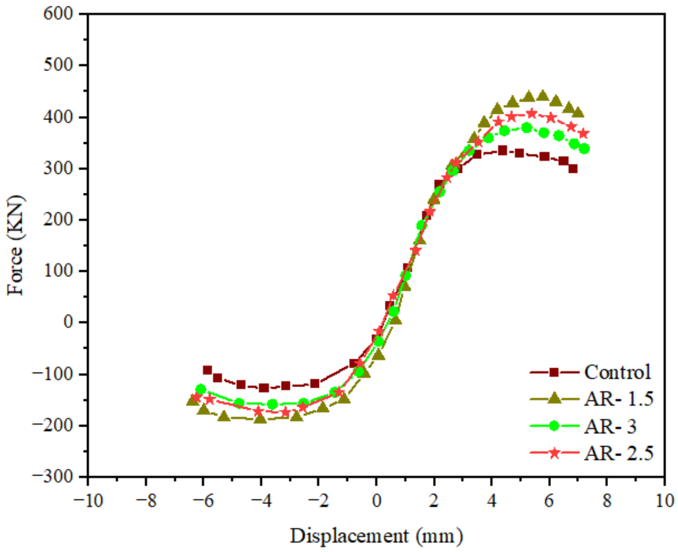

***Figure 4**. Load-displacement cyclic response plot of simulated specimen with various aspect ratio.*

***Table 6**. Summary of peak load capacities for aspect ratio of composite beam.*

Specimen	Peak load (KN)		Average peak load (KN)	∆(mm)		Increase in peak load (%)		Average increase in peak load (%)
	Push	Pull		Push	Pull	Push	Pull	
	(+)	(-)		(+)	(-)	(+)	(-)	
Control	365	120	242.50	8.34	7.72	-	-	-
AR- 1.5	470.5	210.43	340.65	7.34	7.78	105.5	90.43	97.71
AR- 2.5	420.88	202.62	311.75	7.45	7.35	55.88	82.62	69.25
AR- 3	360.85	160.43	260.64	8.15	7.89	-4.15	40.43	18.29

Effect of Span to Depth Ratio on stiffness degradation

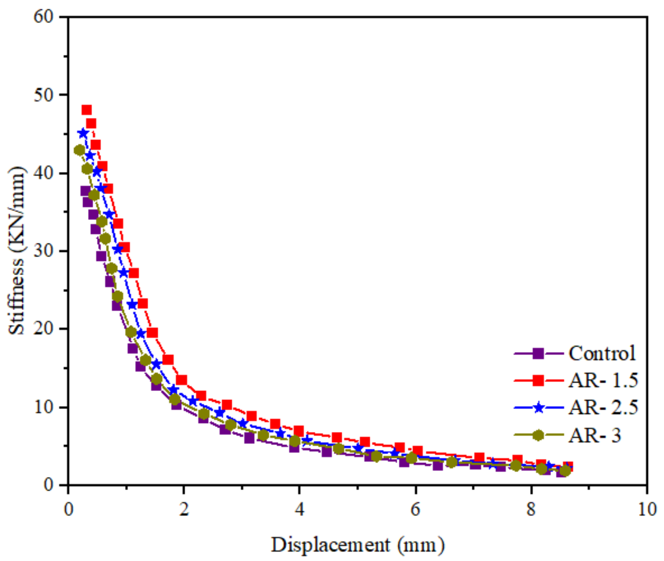

***Figure 5**. Stiffness degradation in terms of span to depth ratio.*

Effect of Span to Depth Ratio on energy dissipation

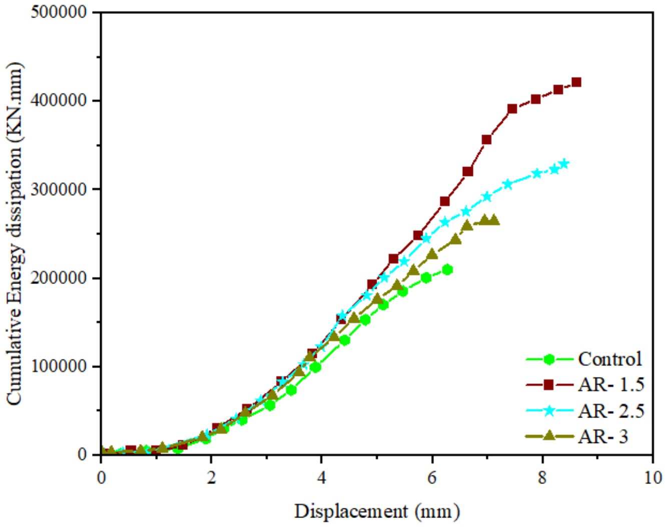

Figure 6. *Energy dissipation in terms of span to depth ratio.*

Result based on Shear Stud Configuration

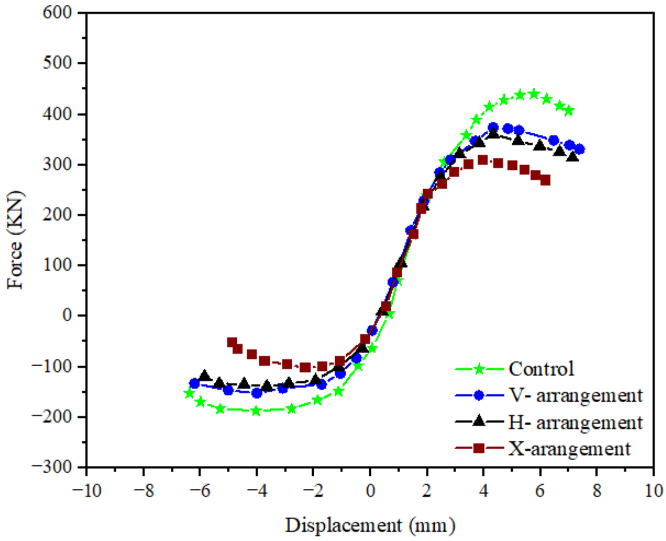

Figure 7. *Load-displacement cyclic response plot of simulated specimen with shear stud configuration.*

Table 7. *Summary of peak load capacities for shear stud configurations.*

Specimen	Peak load(KN) Push (+)	Pull (-)	Average peak load (KN)	Δ(mm) Push (+)	Pull (-)	Increase in peak load (%) Push (+)	Pull (-)	Average increase in peak load (%)
Control	365	120	242.50	8.34	7.72	-	-	-
V- Orientation	342.55	115.44	228.99	7.02	7.40	-22.45	-5.44	-13.94

Specimen	Peak load(KN)		Average peak load (KN)	Δ(mm)		Increase in peak load (%)		Average increase in peak load (%)
	Push	Pull		Push	Pull	Push	Pull	
	(+)	(-)		(+)	(-)	(+)	(-)	
H- Orientation	330.65	104.22	217.43	7.95	7.21	-34.35	-16.22	-25.28
X- Orientation	312.45	95.06	203.76	8.21	8.02	-52.55	-25.06	-38.08

Effect of Shear Stud Configuration on stiffness degradation

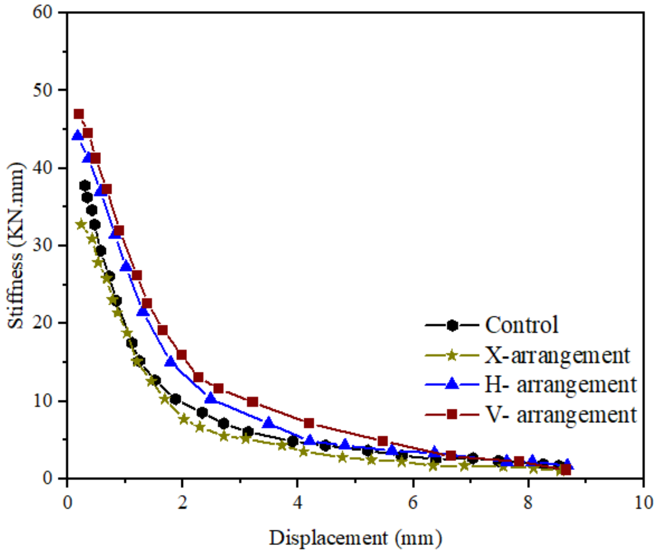

Figure 8. *Stiffness degradation in terms of shear stud configuration.*

Effect of Shear Stud Configuration on energy dissipation

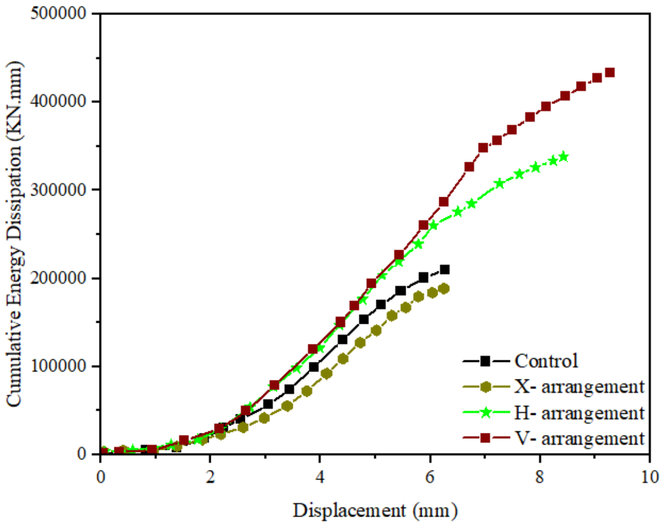

Figure 9. *Energy dissipation in terms of shear stud configuration.*

Result based on Doubler Plate Thickness

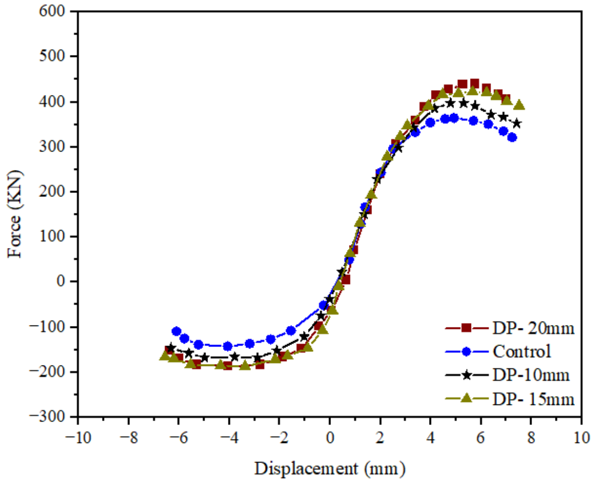

***Figure 10**. Load-displacement cyclic response plot of simulated specimen with doubler plate thickness.*

***Table 8**. Summary of peak load capacities for doubler plate thickness.*

Specimen	Peak load (KN)		Average peak load (KN)	Δ(mm)		Increase in peak load (%)		Average increase in peak load (%)
	Push (+)	Pull (-)		Push (+)	Pull (-)	Push (+)	Pull (-)	
Control	365	120	242.5	8.34	7.72	-	-	-
DP-10 mm	360.51	165.47	262.99	7.75	7.82	-4.49	45.47	20.49
DP-15 mm	390.74	185.65	288.19	7.34	7.65	25.74	65.65	45.69
DP-20 mm	410.55	195.88	303.22	7.22	7.4	45.55	75.88	60.72

Effect of Doubler Plate Thickness on stiffness degradation

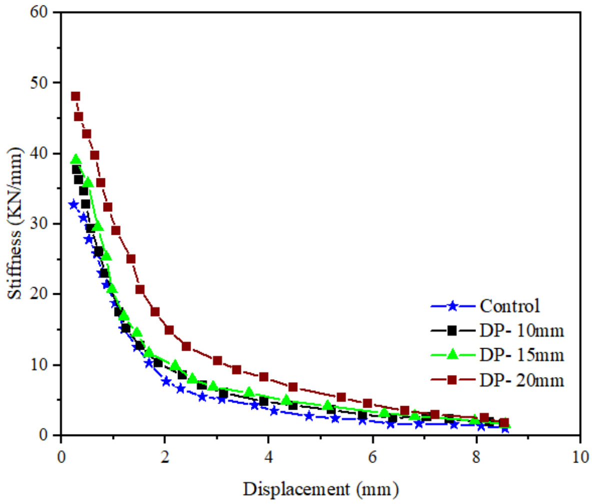

***Figure 11**. Stiffness degradation in terms of doubler plate thickness.*

Effect of Doubler Plate Thickness on energy dissipation

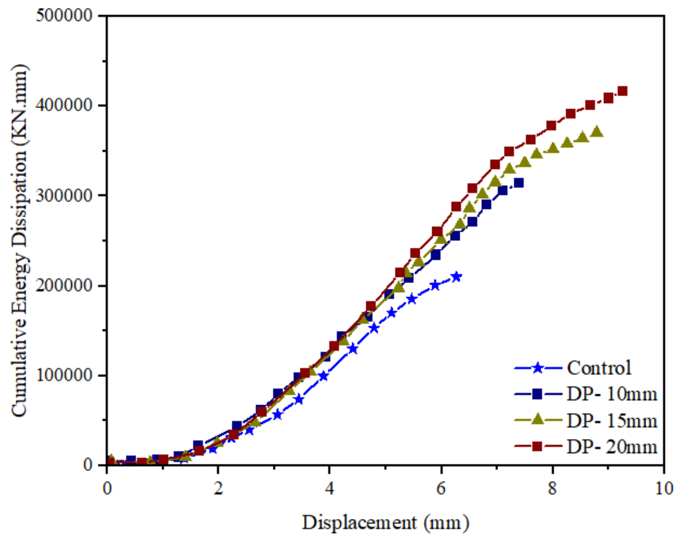

Figure 12*. Energy dissipation capacity in terms of doubler plate thickness.*

4. Discussion

Result based on Composite Beam Span to Depth Ratio

The backbone curve shows that the specimen with an aspect ratio of 1.5 exhibits higher resistance to the applied load compared to those with aspect ratios of 2.5 and 3, although it has a lower load resistance than the control specimen. Conversely, the AR-3 specimen demonstrates lower resistance, indicating a failure mode that signals approaching collapse. A ductile structure with higher load capacity is generally preferred in seismic zones, as it better tolerates deformations and provides warning signs before failure.

The backbone curve shows that the specimen with an aspect ratio of 1.5 exhibits higher resistance to the applied load compared to those with aspect ratios of 2.5 and 3, although it has a lower load resistance than the control specimen. Conversely, the AR-3 specimen demonstrates lower resistance, indicating a failure mode that signals approaching collapse. A ductile structure with higher load capacity is generally preferred in seismic zones, as it better tolerates deformations and provides warning signs before failure.

Effect of Span to Depth Ratio on stiffness degradation

Cyclic secant stiffness diminishes as drift increases, primarily due to concrete cracking and plastic hinge formation. Compared to the control specimen, the AR-3 specimens experienced a slower rate of stiffness degradation throughout the displacement cycles. However, after reaching the ultimate load drift ratio, the degradation stabilized and was comparable to that of the control specimen, indicating better stiffness retention in the AR-3 configuration during maximum displacements.

Effect of Span to Depth Ratio on Energy dissipation capacity

All specimens degenerate similar amounts of energy up to a drift ratio of 1%. Beyond this point, energy dissipation increased more significantly with larger drifts. The specimen with a lower span-to-depth ratio (AR-2) exhibited higher energy dissipation capacity compared to the AR-3 specimen. The control specimen, with the smallest span-to-depth ratio, also showed the least energy dissipation overall. This suggests that beams with lower span-to-depth ratios tend to perform better under seismic loads, offering improved energy dissipation and potentially enhanced seismic resilience.

Result based on shear stud configuration

The V-arrangement of shear studs offers higher resistance to the applied load than the H- and X-arrangements tested in the study. However, this configuration still exhibits lower load resistance compared to the control specimen, indicating that while the V-arrangement improves performance over other stud arrangements, it doesn't surpass the baseline performance of the control.

Effect of Shear Stud Configuration on stiffness degradation

V-arrangement of shear studs exhibited higher peak-to-peak stiffness compared to the control specimens. The stiffness degradation primarily occurred during the initial loading cycles, after which the stiffness values stabilized. Beyond a 4% drift ratio, the stiffness levels across different arrangements were roughly similar, indicating that the influence of stud arrangement on stiffness diminishes at larger deformations.

Effect of Shear Stud Configuration on Energy dissipation capacity

The V-arrangement of shear studs achieves higher energy dissipation capacity compared to the X-arrangement. The X-arranged specimens recorded poorer performance in absorbing seismic energy, indicating that the V-shape configuration is more effective for energy dissipation, which is beneficial for seismic resilience.

Result based on Doubler Plate Thickness

Increasing the doubler plate thickness results in a more ductile hysteresis response, with reduced rotational and shear capacity compared to thinner plates. This behavior reflects different failure modes: more ductile, flexural-induced shear failure in specimens with thinner plates, and brittle shear failure in those with larger plates. The thicker plates enhance ductility but at the cost of overall shear capacity.

Effect of Doubler Plate Thickness on stiffness degradation

The specimen with the thickest doubler plate (DP-20 mm) exhibited a higher peak-to-peak stiffness at lower drift ratios compared to specimens with thinner doubler plates (DP-10 mm). This indicates that stiffness degradation had a significant influence during the initial loading cycles. After a 4% drift ratio, the stiffness values were approximately the same across all specimens, regardless of doubler plate thickness.

Effect of Doubler Plate Thickness on Energy dissipation capacity

The energy dissipation of specimens DP-10 mm, DP-15 mm, and DP-20 mm becomes progressively larger compared to the control specimen. Furthermore, the results indicate that the composite beam with the thickest doubler plate (DP-20 mm) exhibits a higher energy dissipation capacity than the specimen with the thinnest doubler plate (DP-10 mm). In general, increasing the doubler plate thickness improves the performance of the composite steel beam under seismic loading.

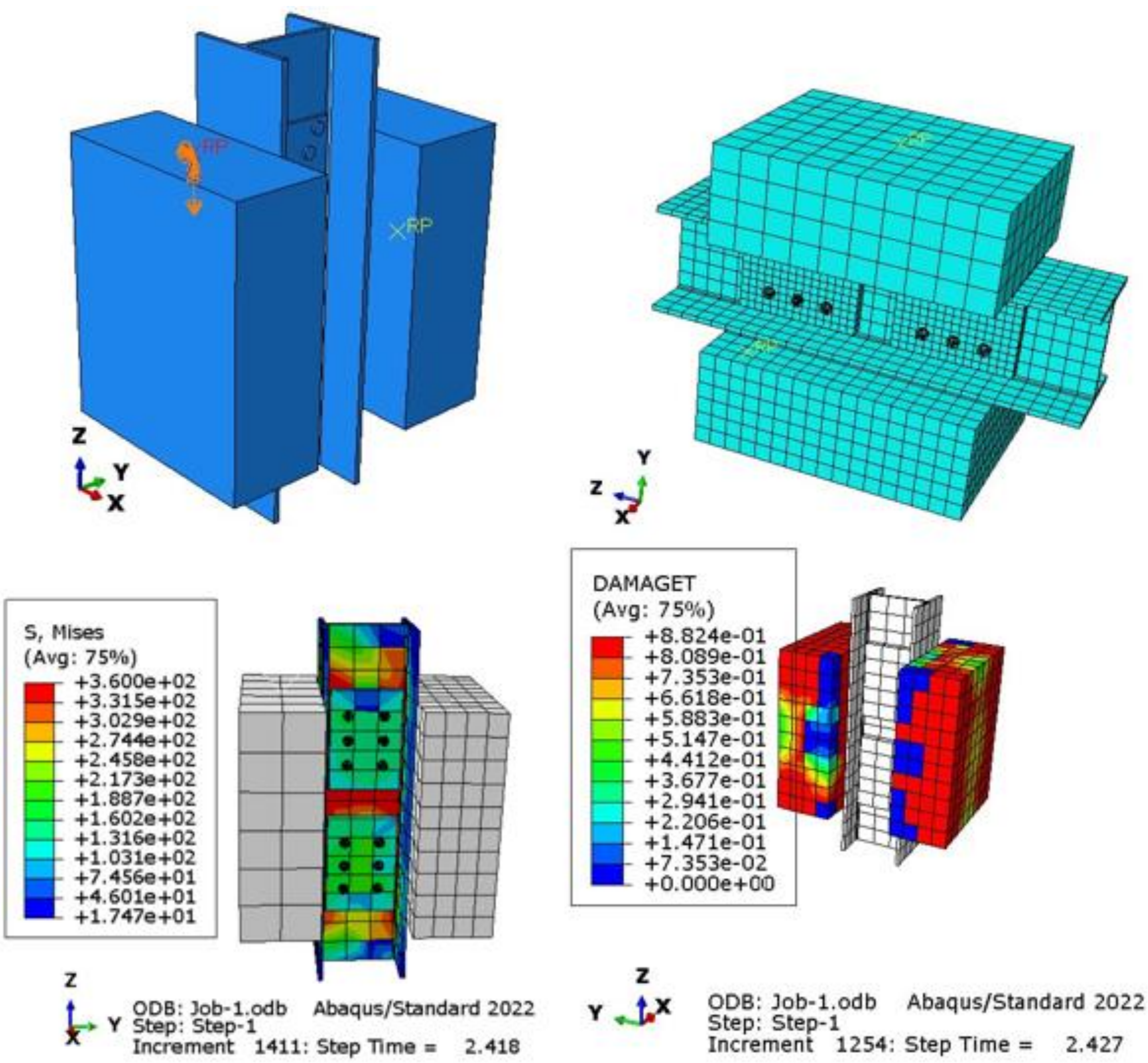

Figure 13. *Loading, meshing and analysis result.*

5. Conclusion

The following conclusions were drawn based on the results of the nonlinear finite element simulations conducted using ABAQUS:

1) The assessment between the finite element model and experimental results demonstrated a good agreement, validating the model's ability to accurately predict the cyclic behavior of composite beams.
2) The validation of the numerical model showed slightly higher initial stiffness in the cyclic response compared to experimental data; however, overall trends were consistent, confirming the model's reliability.
3) Among the different shear stud configurations studied, the V-shaped arrangement exhibited superior load resistance compared to H- and X-shaped arrangements, although it performed slightly below the control specimen. However, the V-configuration showed higher peak-to-peak stiffness and energy dissipation capacity, while the X-configuration had the lowest energy dissipation.
4) Increasing the doubler plate thickness enhanced the beam's maximum load resistance but reduced its rotational capacity. Specimens with a thicker doubler plate (DP-20) demonstrated higher initial stiffness and lower stiffness degradation, which are desirable properties under seismic loading.
5) The DP-20 specimen also exhibited greater energy dissipation compared to the thinner DP-10 specimen, indicating improved seismic performance with increased doubler plate thickness.
6) Regarding span-to-depth ratios, an increase in this ratio led to higher ductility but reduced rotational and shear capacities. The lower span-to-depth ratio (AR-2) demonstrated superior energy dissipation capabilities.

Abbreviations

ACI	American Concrete Institute
AR	Aspect Ratio
CDP	Concrete Damaged Plasticity
DP	Doubler plate
FEA	Finite Element Analysis
H	Horizontal
V	Vertical
X	Cross Arrangement

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Conflicts of Interest

The authors declare no conflicts of interest.

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