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Numerical Analysis of Shear Capacity of Double Corrugated Web Girder Infilled Concrete

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Abstract

This research investigates the shear capacity of double corrugated web steel I-girders filled with concrete using finite element analysis. The study examines the influence of the corrugation angle and the thickness of the concrete filling on the strength capacity of the girder beams. Four beams were designed to fail in shear along a 1500 mm span from the left support of the beam, enabling the determination of shear failure conditions. Each beam had identical properties with a flange width (B) of 250 mm, a web height (H) of 1000 mm, a span length of 3500 mm, a flange thickness (tf) of 15 mm, and a web thickness (tw) of 1 mm. The research employed a 3-point bending method, applying a single load point 1500 mm from the left support. The tests were conducted by varying the corrugation angles and the thickness of the concrete filling in the corrugated web, which served as the research variables. The study aimed to determine the peak load-deflection curve, the failure mode diagram, and the shear capacity of the girder beams. The results of the tests showed that the double corrugated web steel I-girder filled with concrete, with a corrugation angle of 45 degrees and a concrete thickness of 65 mm, exhibited the best load-bearing strength among the three variations tested. It demonstrated a 52.65% increase in load capacity and a 53.49% reduction in deflection compared to the finite element validation test values. In contrast, the other three variations showed a decrease in shear strength.

Keywords
Steel girder, corrugated web I-Girder, double corrugated web concrete filled Girder, ABAQUS, shear capacity

INTRODUCTION

Steel is one of the materials commonly used in construction because it is considered easier and faster to work with compared to concrete structures[1]. One popular application of steel in construction is in bridge structures, where I-girder plates are a primary choice. I-girder plates have a higher cross-sectional dimension compared to conventional I-girder beams, providing a greater moment of inertia, which is crucial for bearing bending loads[2], [3].

However, one of the drawbacks of I-girder plates is their slender dimensions, which make them more prone to buckling[4]. To address this issue, an innovative solution is known as the Corrugated Web I-Girder has been introduced. Corrugated Web I-girders effectively reduce the risk of buckling without the need for vertical stiffeners in conventional I-girders[5].

The main advantage of Corrugated Web I-girders is their ability to increase the girder's strength while reducing the amount of steel used. Studies have shown that the use of corrugated webs can enhance the girder's strength with a reduction in steel weight by about 9-13% compared to conventional I-girders[6], [7]. In the absence of vertical stiffeners, the weight of the beam is reduced without compromising its strength and obtaining a cost reduction of about 30%[7]. This makes Corrugated Web I-Girders an efficient and economical alternative in bridge construction, allowing for designs that are lighter yet still strong and stable[4], [8].

In addition to increasing the shear strength in resisting loads, the use of corrugated web I girder plates can also .provide additional aesthetic value to a building structure than using conventional I girders[9]. This innovation has been applied to several bridges abroad such as the Hontani Bridge completed in Japan in 1998, the Maupre Bridge, and the Dole Bridge completed in France in 1987 and 1995[9] - [12].

There is a new innovation in the research of corrugated web steel girders where the flange is made tubular and filled with concrete[13], [14]. The results indicate that the concrete enhances the stiffness of the girder flange, making the girder beam less susceptible to flange buckling[13], [14].

Research into composite I-girder beams with single and double corrugated webs without concrete infill has also progressed [15]. The findings indicate that using a single corrugated web is more efficient in flexural shear resistance compared to a double corrugated web of the same thickness. Therefore, the use of double corrugated steel plate I-girders without concrete infill is not recommended[15], [16].

This discovery was subsequently utilized by Kristijanto et al. (2022), who conducted experimental tests on several girder beams, including a double corrugated web girder filled with concrete, with anchors installed at various vertical positions to prevent outward buckling[1]. The test results showed that the Double Corrugated Web Girder Infilled with Concrete and 3 Anchors exhibited significantly higher local buckling resistance compared to single-profile steel girders without stiffeners.

Research on corrugated web I-girder plates continues to evolve, from simple designs to more complex profiles, in search of the ideal form of corrugated web I-girders for load-bearing. Therefore, this study aims to develop several modified profile shapes of corrugated web I-girders based on variations in the corrugation angle using Finite Element Analysis. This method can expedite the testing of profile shape modifications and provide a diverse range of results.

RESEARCH SIGNIFICANCE

This study aims to Analyze the shear capacity of a double corrugated web girder with filled concrete through static loading with variations in bending angle and filler concrete thickness.

METHODOLOGY

The method used in this research involves performing finite element analysis on corrugated web steel girders with dimensions of 250x1000x3500 mm. The main focus of this study is on the load-deflection curve, crack patterns, and shear capacity.

A. COLLECTION OF TECHNIQUE DATA

In this study, a finite element analysis of five models was carried out where one model is a model for validation of experimental test results while the other four models are variations of the validation model. The test specimen model used for validation is the test specimen in the experimental research of Kristijanto et al. (2022) which is a steel girder profile with double corrugated web girder infilled concrete with 3 anchors (Double Corrugated Web Girder infilled Concrete with 3 Anker/DCWGIC-3A). The I-Girder specimens will have 6.5 waves each with a body length (L) of 3500 mm and body height (hw) of 1000 mm, with a concrete thickness (tw) of 50 mm and a web thickness (tw) of 1 mm each. While the thickness of the wing plate is 15 mm and the width of the wing is 250 mm. then the I-Girder body is given 3 stiffener on each vertical side with a thickness of 10 mm.

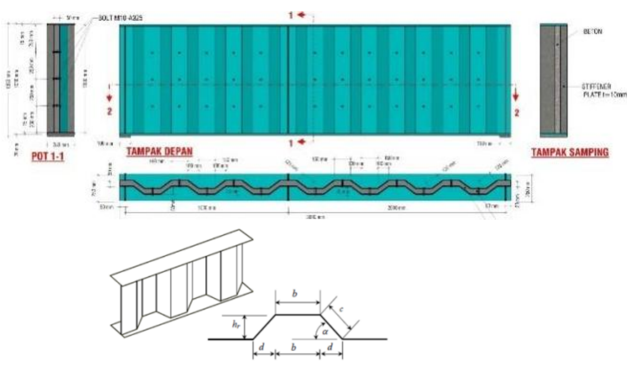


Figure 1 Configuration of Corrugated Web Girder Type *DCWGIC-3A (Source: Kristijanto, et al, 2022)*

At both pedestals and under centered load, stiffeners with a thickness of 10 mm are installed as shown in Figure 1 [3]. while the details of the corrugated body configuration are presented in Table 1.

Table 1 Detail Configuration of Corrugated Web

Specimen	b (mm)	c (mm)	d (mm)	hr (mm)	α (°)	n Anchor
DCWGIC-3A	150	125	100	75	36,87	3

(Sumber: Kristijanto, et al,. 2022)

Furthermore, the other four variation models have the same girder beam dimensions as the validation model but have variations in wave bending angle and corrugated web [17]. The configuration details of the variation girder beams can be seen in Table 2.

Table 2 Variation of Test Objects Based on Bending Angle and Thickness of Corrugated Web Concrete

Type of Girder	b (mm)	c (mm)	d (mm)	hr (mm)	α (°)	Thickness of Concrete (mm)
T-S1	150	141,4	100	100	45	50
T-S2	150	115	80	138,6	60	50
S-T1	150	141,4	100	75	36,87	35
S-T2	150	141,4	100	75	36,87	65

In this analysis, the material properties for the steel used include the modulus of elasticity of the steel (E) used of 210,000 MPa, Poisson's ratio (*v*) used of 0.3 and the yield stress of the steel (fy) of 240 MPa, the ultimate stress of the steel (fu) 370 MPa, and the specific gravity of the steel of 7850 kg/cm^2 or equivalent to 2x10-5 N/mm^3 while for the concrete material used is compressive strength of 650 kg/cm2 aged 28 days or equivalent to 66 MPa. The Poisson's ratio of concrete (v) was 0.2 and the specific gravity of concrete was 2400 kg/cm^3 or equivalent to 7.85x10-5 N/mm^3.

B. TECHNIQUE ANALYSIS OF FINITE ELEMENT

The analysis used in this research is Abaqus finite element analysis. In modeling using Abaqus software, the first step undertaken is modeling each element using the "part" module, followed by assembling them using the "assembly" module[18]. The materials used in this research consist of concrete and steel, with their respective properties adjusted based on previous studies, particularly those conducted by Kristijanto, et.al. 2022 [19]. Details of the materials used are listed in Tables 3 and 4.

Table 3 Material of steel

Density (kg/m^3)	Elastic (Mpa)	Fy (Mpa)	Poisson ratio
7850	210000	240	0.3

Table 4 Material of concrete

Density (kg/m^3)	Elastic (Mpa)	Fc' (Mpa)	Poisson ratio
2400	35794,134	66	0.2

In Abaqus, to simulate concrete damage, the CDP (Concrete Damaged Plasticity) method can be used. The main parameters that need to be defined in the CDP model are dilation angle (ψ), eccentricity (ε), K value, uniaxial compressive strength ratio (fb0/fc0), and viscosity (μ) [20] - [23]. The values of these parameters are shown in the table 5.

Table 5 Parameter value of Concrete Damaged Plasticity (CDP)

Angle of dilation (ψ)	Eccentricity (ε)	K	compressive strength comparison (fb0 /fc0)
36	0.1	2/3	1.16

The interaction module is one of the features found in Abaqus that serves to determine the contact area between part surfaces and to determine the type of interaction experienced by the model.

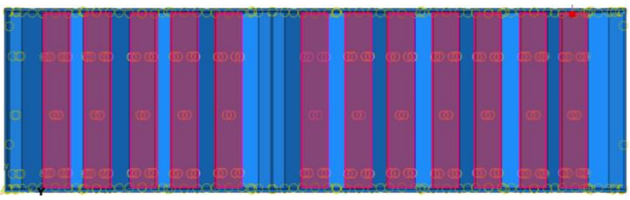


Figure 2 Constraints-tie type Interaction Input Model in Abaqus

The interaction in this model connects steel with steel, and steel with concrete by using constraints-tie which serves to bind two separate surfaces so that there is no relative movement between them. In addition, constraint-tie-type interactions can also be used for models that have different mesh areas. constraints-tie is placed on the parts of the web where there are anchors instead of anchor models.

The loading in this analysis is a static loading where a single load is placed at a distance of 1500 mm from the left side of the girder beam. The load applied in the model is a displacement load of 25 mm. The support conditions for the girder beam use a pin-roller support configuration.

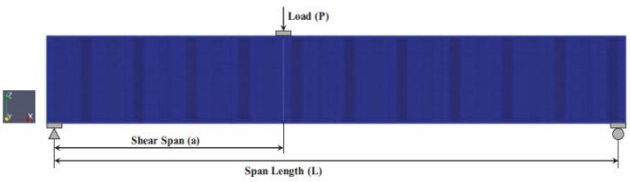


Figure 3 Corrugated Web I-Girder steel model (Kristijanto et al., 2022)

RESULTS AND DISCUSSIONS

A. LOAD DISPLACEMENT

The result of the finite element analysis includes the Peak Load-Displacement curve shown in Figure 3. Each result from the variation models is compared with the validation model. From Figure 3 and Table 3, it is known that the T-S1 girder type shows the highest peak load value of 100.97 tons with a displacement of 6.35 mm. The peak load value of the T-S1 girder type is 8.73% higher than the peak load of the validation girder model, while the displacement value of the T-S1 girder type is 53.49% lower than the displacement of the validation girder model. This indicates that the T-S1 girder type is stiffer than the validation girder model, resulting in a higher peak load value for the T-S1 girder type compared to the validation girder model. On the other hand, the three other variation models show lower peak load-displacement values compared to the validation girder model.

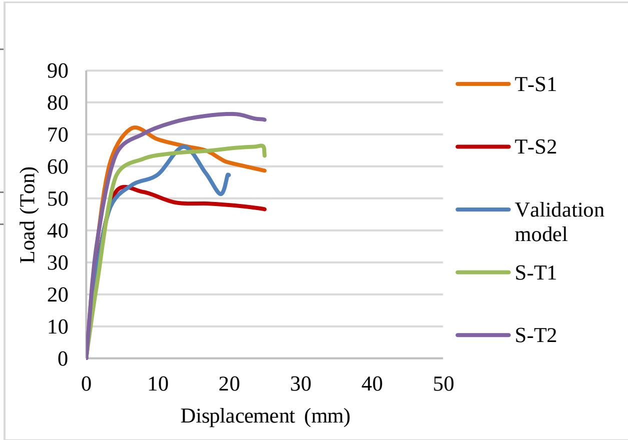


Figure 4 Load-Displacement Curve

Table 6 Load-Displacement

Type of Girder	Peak Load (Ton)	Displacement (mm)
Validation Model	66.15	13.65
T-S1	71.92	6.35
T-S2	52.07	7.94
S-T1	66.34	24.79
S-T2	76.40	20.92

B. FAILURE PATTERN

Steel Failure

The failure of steel can be identified by the PE value, or plastic strain component, which is the plastic strain occurring in the steel material in Abaqus, as shown in Figures 4 to 7. Plastic strain (PE) represents the change in size or shape of the material under load, and when the load is removed, the material cannot return to its original shape. Plastic strain is reached when the steel has attained the yield strain of 0.0012 mm/mm. Plastic strain lies between the yield strain and the ultimate strain of the steel, which is 0.2108 mm/mm. This strain value is obtained by dividing the steel's tensile strength by the modulus of elasticity of the steel, which is 200,000 MPa.

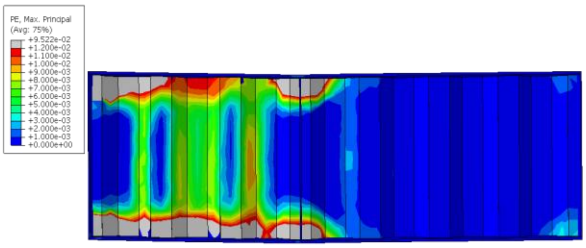


Figure 5 Plastic Strain Distribution of Steel (PE) Model DCWGIC-3A

From these various models below, it can be observed that the larger the angle of bending from a corrugated web girder, the more the failure tends to concentrate at a specific point rather than spreading evenly. This causes the steel to fail more quickly, reducing the girder's ability to bear loads.

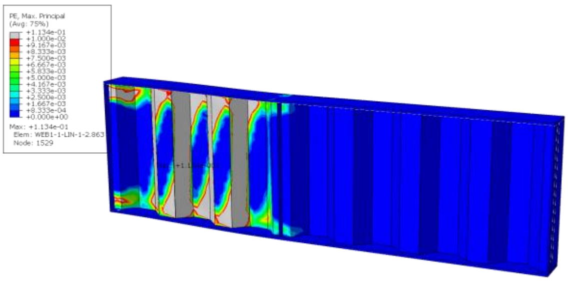


Figure 6 Plastic Strain Distribution of Steel (PE) Model T-S1

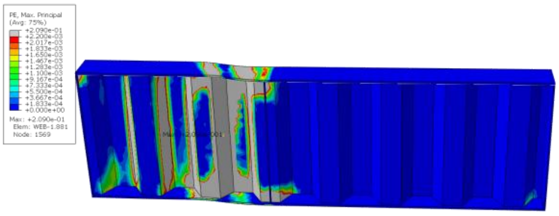


Figure 7 Plastic Strain Distribution of Steel (PE) Model T-S2

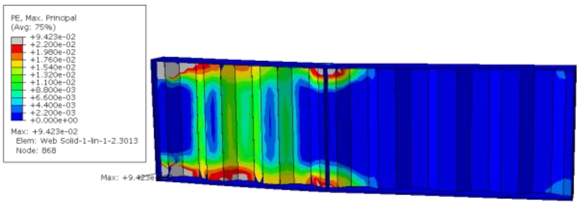


Figure 8 Plastic Strain Distribution of Steel (PE) Model S-T1

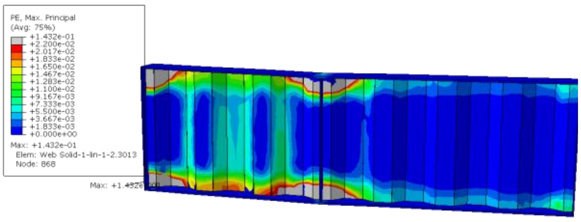
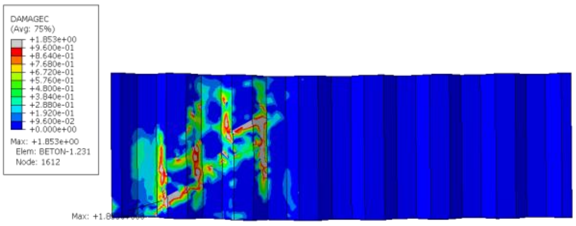


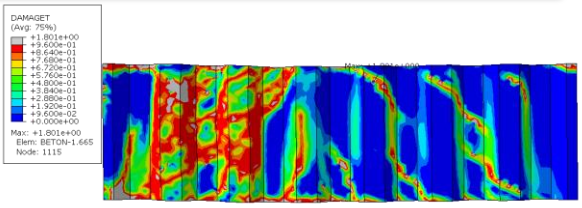
Figure 9 Plastic Strain Distribution of Steel (PE) Model S-T2

Concrete failure

Failure in concrete within Abaqus is divided into compressive damage (DamageC) and tensile damage (DamageT) [20], [24]. The first crack in the T-S1 girder type occurs at 0.2 seconds with the load carried by the girder being 28.89 kN and the displacement being 1.16 mm. From the figure, it is known that the T-S1 girder type has failed because the concrete damage value has reached 1.

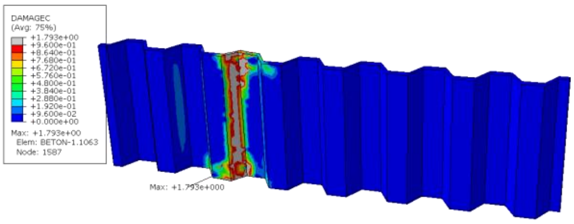


(a) Damage Compressive of Concrete

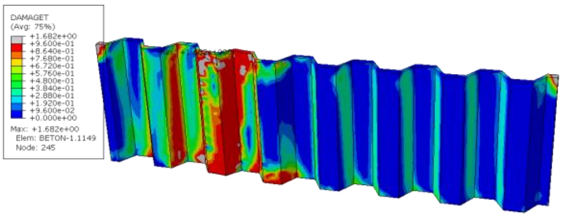


(b) Damage Tension of Concrete

Figure 10 Concrete damage of girder type T-S1



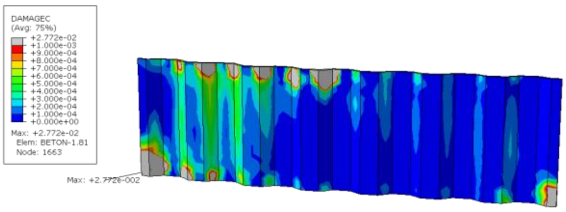
(a) Damage Compressive of Concrete



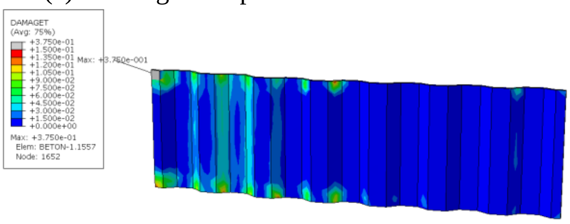
(b) Damage Tension of Concrete

Figure 11 Concrete damage of girder type T-S2

The distribution of damage to the concrete due to compression and tension in the T-S2 model, with the angles 60° shown in Figure 11. Indicates that the first cracks in the compression and tension areas occurred at a load of 52 tons and a deflection of 7.9 mm. When the analysis concluded, the concrete damage values were above 1, indicating that the concrete had completely failed. The cracks in this model tend to be vertical, caused by excessively steep wave buckling, preventing the crack pattern from distributing evenly across the surface of the other sections and leading to concentration at one buckle. This condition affects the girder's ability to bear the load, as the load cannot be evenly distributed across the girder's body, causing certain parts to fail first while other parts remain intact. This results in the girder's load-bearing capacity being less than optimal, ultimately leading to a lower overall strength of the girder.



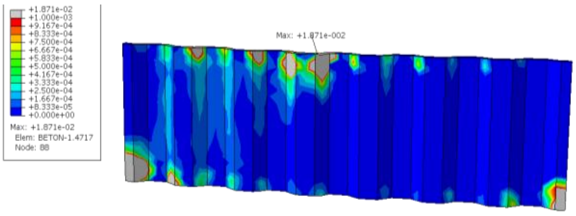
(a) Damage Compressive of Concrete



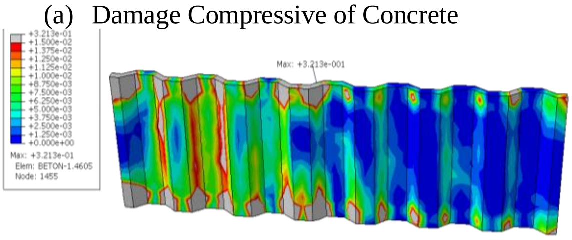
(b) Damage Compressive of Concrete

Figure 12 Concrete damage of girder type S-T1

Figure 12 presents the damage diagram of the compression area (DamageC) and the tension area (DamageT) for the S-T1 model with a concrete thickness of 35 mm. The first cracks in both the compression and tension areas occurred at a load of 52 tons and a deflection of 7.9 mm. The concrete damage values in both the tension and compression areas of the S-T1 model are below 1, indicating that the concrete has cracked but has not completely failed.



(a) Damage Compressive of Concrete



(b) Damage Compressive of Concrete

Figure 13 Concrete damage of girder type S-T2

The distribution of damage to the concrete due to compression and tension in the S-T2 model, with a concrete thickness of 65 mm shown in Figure 13. The figures indicate that the first cracks in the compression and tension areas occurred at a load of 35.18 tons and a deflection of 1.45 mm. When the analysis concluded, the concrete damage values were below 1, indicating that the concrete had cracked but had not completely failed.

C. SHEAR CAPACITY

Table 7 compares the shear capacity of corrugated web girders from finite element validation specimens with variation specimens [25]. Through this comparison, the increase or decrease in the shear capacity of the girder from its original form can be determined. For the T-S1 type girder, there is an increase in shear capacity of 8.73%, whereas the T-S2 type girder shows a decrease in shear capacity of 21.29%. Additionally, the S-T1 type girder has a shear capacity value almost identical to the validation model, with an increase of just 0.29%. In contrast, the S-T2 type girder shows an increase in shear capacity of 15.49%.

Table 7 Shear Capacity Of Several Girder Models

Type of Girder	Shear Capacity (Ton)	Validation model (Ton)	Vu Variation/Vu validation
T-S1	41.10	37.80	1.09
T-S2	29.75		0.79
S-T1	37.91		1.00
S-T2	43.65		1.15

This indicates that the choice of the bending angle and concrete thickness directly influences the shear capacity of the beam. A larger bending angle of the corrugated web decreases the shear capacity of the girder beam, whereas increasing the concrete thickness tends to enhance the shear capacity.

CONCLUSIONS

This study aims to analyze the shear capacity of a double corrugated web girder with filled concrete through static loading with variations in bending angle and filler concrete thickness. The study was conducted through nonlinear finite element analysis. Based on the results, several conclusions can be drawn.

1. The validation results between experimental testing and finite element analysis show nearly identical peak load values. The experimental result indicates a load of 63.590 tons at a deformation of 3 mm, while the Finite Element analysis shows a maximum load the girder beam can withstand is 66.15 tons occurring at 13 mm of deformation, with a peak load difference of only 0.04%.
2. Corrugated steel girders filled with concrete, with a wave bending angle of 45°, exhibit better load-bearing strength compared to variations with a 60° wave bending angle. The specimen with a 45-degree angle shows an increase in peak load of 8.73%, whereas the specimen with a 60-degree angle experiences a decrease in peak load of 21.29% compared to the validation specimen. This is because a larger wave bending angle causes the load to be unevenly distributed across the entire structure, resulting in stress concentration at specific points.
3. Variations using a concrete thickness of 65 mm demonstrate higher load-bearing strength with an increase in peak load of 10.25%, while variations with a 35 mm thickness experience only a slight increase of 0.29% in peak load.

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