NONLINEAR FE ANALYSIS OF PLATE GIRDERS WITH SINUSOIDALLY CORRUGATED WEB TO INVESTIGATE LATERAL TORSIONAL BUCKLING BEHAVIOUR

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ABSTRACT

Corrugated web girders (CWGs) have emerged as a lightweight and efficient alternative to conventional flat-web plate girders (FWPGs), offering high strength-to-weight ratios, improved ductility, and enhanced shear resistance. Among various profiles, sinusoidal corrugations are particularly attractive due to their favorable structural performance and ease of fabrication. While the flexural and shear behavior of Sinusoidally Corrugated Web Plate Girders (SCWGs) has been extensively studied, research on their lateral-torsional buckling (LTB) resistance remains limited, despite its critical influence on the global stability of slender girders. This paper presents a three dimensional finite element (FE) study that incorporates both geometric and material nonlinearities. The model has been validated against past experimental studies on plate girders with sinusoidal corrugation. Comparisons of deformation patterns and load–displacement responses demonstrated strong agreement between numerical and experimental results, confirming the reliability of the simulation. The validated model provides a robust basis for an in-depth parametric study to quantify the influence of geometric parameters and to compare the LTB performance of SCWGs with that of FWPGs. Furthermore, it offers a pathway toward optimization-based approaches for identifying efficient corrugation parameters that balance weight reduction with improved lateral torsional buckling resistance.

Keywords *Sinusoidally Corrugated Web Plate Girders (SCWGs),Flat Web Plate Girders (FWPGs) Lateral Torsional Buckling (LTB), Nonlinearity, Finite Element (FE) Model.*

1. INTRODUCTION

A need for lightweight, efficient, and structurally sound girders has led to the development of corrugated web girders (CWGs). These are widely used in long-span bridges, commercial buildings (Figure 1), and other demanding applications, offer enhanced shear resistance and reduced weight. The sinusoidal corrugated web is one of the most effective structural configurations, distinguished by its continuous wave-like pattern, which ensures a uniform stress distribution and significantly reduces localized stress concentrations (Pasternak and Kubieniec, 2010; Hannebauer, 2008).

(a) Construction Stage (b) Final Stage

Figure 1: SCWGs in Mercedes Benz Queensway, Toronto.

Research on corrugated web girders (CWGs) has largely focused on their flexural and shear behavior. Due to the accordion effect, the web contributes little to moment resistance, while the flanges carry most of the load, resulting in improved ductility and reduced material demand compared with flat web girders (FWGs) (Al-Kanon, 2019). Shear resistance is also significantly enhanced by corrugation, which delays web buckling and allows the use of thinner plates. Experimental studies have confirmed that corrugated webs achieve higher shear capacity and improved buckling stability than flat webs, enabling up to 40% material savings (Sayed-Ahmed, 2005; Leblouba et al., 2022).

In contrast, fewer studies have addressed the lateral-torsional buckling (LTB) behavior of CWGs, even though LTB often governs the design of slender girders. Numerical investigations have demonstrated that corrugation depth and profile strongly influence torsional rigidity, delaying buckling compared with FWGs (Ibrahim, 2014; Sayed-Ahmed, 2005). Large-scale experimental studies on trapezoidal webs further confirmed the sensitivity of LTB resistance to imperfections, flange size, and web thickness (Jager et al., 2022; Zhang et al., 2022).

Research on sinusoidal corrugated webs is more limited, although sinusoidal corrugation provides superior performance compared to other profiles. Hannebauer (2008) reported that sinusoidal corrugations enhance torsional stiffness and delay global instability, while Reinders and Balomenos (2022) validated this experimentally, showing that conventional design equations underestimate the true LTB strength of sinusoidal girders.

The study by Reinders and Balomenos (2022) represents the largest experimental program on sinusoidal corrugated web girders, although only nine tests were conducted. Decisions regarding design recommendations were based on this limited dataset, and the authors suggested further numerical studies to strengthen their findings. In response, the present study develops a three-dimensional finite element model of sinusoidal corrugated web plate girders, incorporating both geometric and material nonlinearities.

2. METHODOLOGY

A three-dimensional finite element (FE) model using ANSYS 19 R2 was developed to study sinusoidally corrugated web plate girders (SCWGs) exhibiting lateral-torsional buckling (LTB) behaviour.

2.1 Modelling Parameters

Modelling parameters were taken from the studies of the mentioned researchers to simulate their experimental studies. The main elements in geometry of plater girder includes the flanges, webs, and web-stiffeners, load transfer device etc. The sinusoidal corrugated web shape was modelled using the equation no. (1)

$$y = a\sin(\frac{2\pi x}{\lambda}) \tag{1}$$

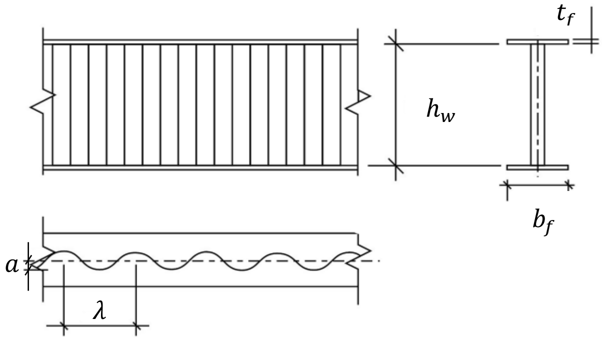


Figure 2: SCWGs configuration

where a = amplitude of the sine wave, λ = corrugation wavelength, x is the distance from starting point of sine function. The other notations are mentioned in figure. 2 where t_f =flange thickness, h_w=web height, b_f =width of the flange.

2.2 Element Modelling

'SHELL181' element was used to model all the components. It is suitable for analysing thin to moderately thick shell structures. SHELL181 geometry (Figure 3) is defined by four nodes having six degrees of freedom at each node: translations in the x, y, and z directions, and rotations about the x, y, and z-axes. SHELL181 is well-suited for linear, large rotation, and/or large strain nonlinear applications.

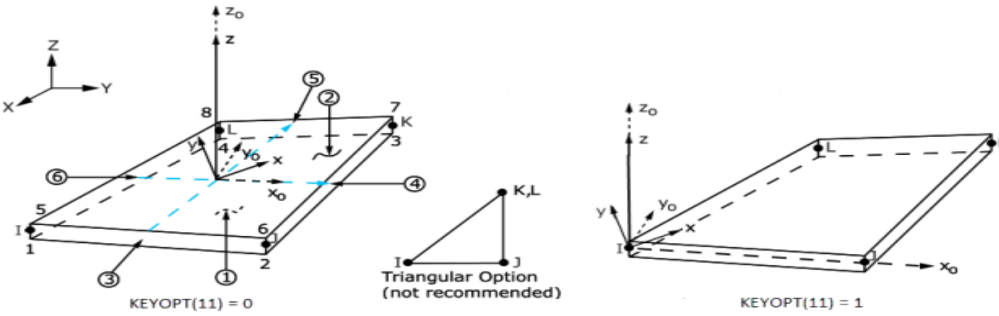


Figure 3: SHELL181 Geometry (ANSYS, Inc. 2019)

2.3 Material Modelling

Steel material behaviour was modelled using a bilinear kinematic hardening rule with the parameters modulus of elasticity (E), Poisson's ratio (v), yield stress (f_y), and tangent modulus (E_T). Both elastic and inelastic buckling behaviour are allowed with this constitutive model.The initial slope of the curve is the elastic modulus of the material and beyond the user-specified initial yield stress σ_0, plastic strain develops, and the back stress evolves so that stress versus total strain continues along a line with slope defined by the user- specified tangent modulus E_T. This tangent modulus cannot be less than zero or greater than the elastic modulus. For uniaxial tension followed by uniaxial compression, the magnitude of the compressive yield stress decreases as the tensile yield stress increases so that the magnitude of the elastic range is always $2\sigma_0$, as shown in figure 4.

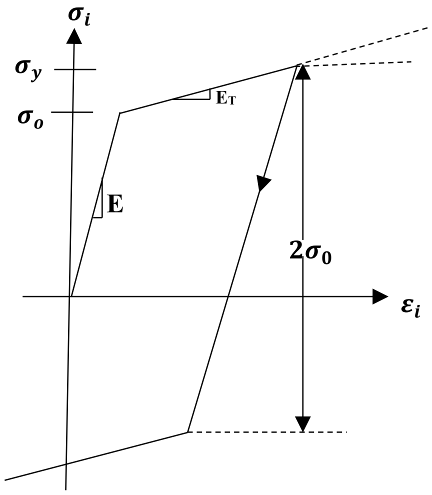


Figure 4: Stress vs Total Strain for Bilinear Kinematic Hardening (Ansys Inc. 2019)

2.4 Generation of Model Geometry

Since a continuous sine function would theoretically require infinite points, a practical approach was adopted by dividing one complete sine wavelength into twelve segments. This segmentation ensures computational efficiency while maintaining geometric accuracy. The equation was discretized into the following form (Equation no. 2) where ns is the segment number along the sine wave.

$$z = a \sin\left(\frac{2\pi}{12} ns\right) \tag{2}$$

After generating the keypoints along the sine wave**,** areas were formed by connecting them systematically. Once the bottom flange was completed, it was replicated to create the top flange. The keypoints forming the sinusoidal web were then joined to construct the corrugated web profile. This approach allowed the creation of a single sine wave of the sinusoidally corrugated plate girder.

To achieve the desired girder length, the single sine wave segment was replicated along the length of the beam. The replication was controlled to ensure that the number of complete sine waves matched the required span length, maintaining an accurate representation of the physical structure. The thickness is added to the specific component after meshing. Figure 5,6,7 shows the generated geometry.

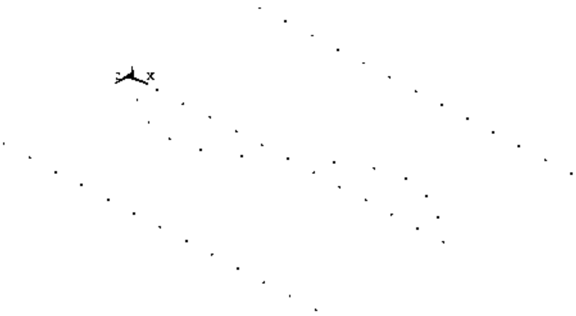


Figure 5: keypoints of bottom flange (One sinewave)

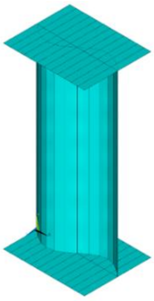


Figure 6: Sinusoidal Corrugated Plate Girder (One sinewave)

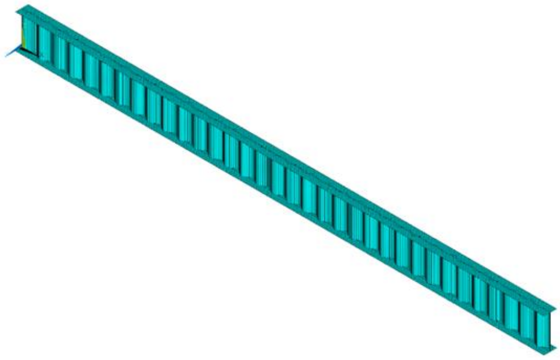


Figure 7: Sinusoidal Corrugated Plate Girder without stiffener and shear tab (Full length)

2.5 Meshing

The meshing of stiffener, flanges, web, and shear tub are done in such a way that the dividing lines of the mesh of each of these parts match with other one or more parts where connected. In this way, thorough connectivity is ensured throughout the whole system. Lines were divided using LESIZE command to ensure proper mesh size. All the elements of the models were meshed using the AMESH command. A smaller mesh of 20 mm sizes was chosen to accurately depict the curvature of the corrugated web. Figure 8 shows isometric view of the girder after meshing.

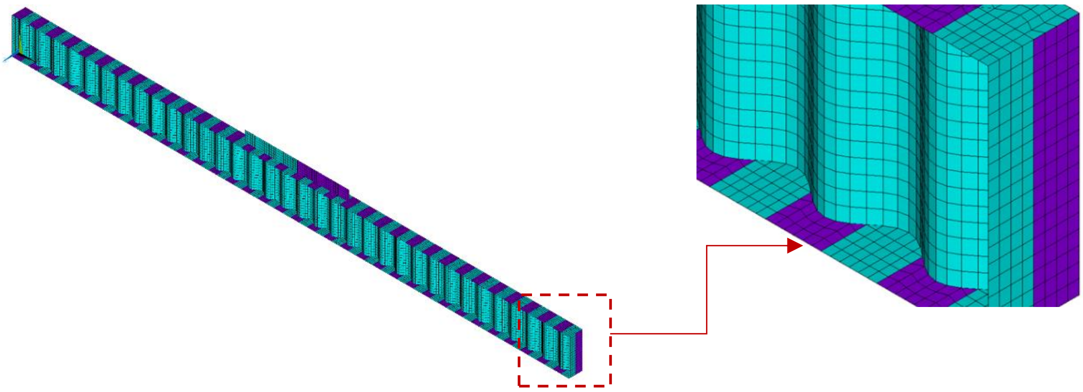


Figure 8: Meshing

2.6 Boundary Conditions and Loading

The boundary conditions are applied to restrict the movement of the beam and to mimic the experimental setup. One end is restricted from translation in the x, y and z directions while one the other end translation is restricted to the y and z axis to the top flange of the girder to simulate a simply supported condition (Figure 9). For the loading procedure a displacement control is used to displace the shear tab in a vertical direction. A static loading procedure is used to apply the displacement (Figure 10). The maximum number of steps was limited to 100 steps to keep a low computational cost.

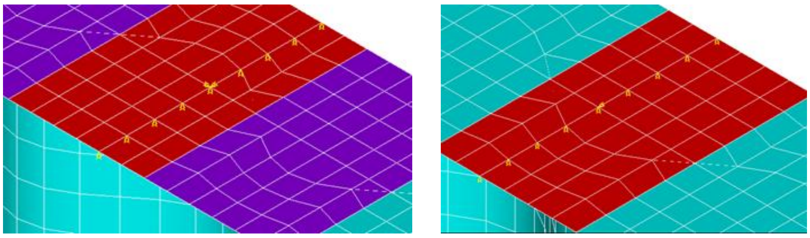


Figure 9: Support Conditions at two ends of the girder

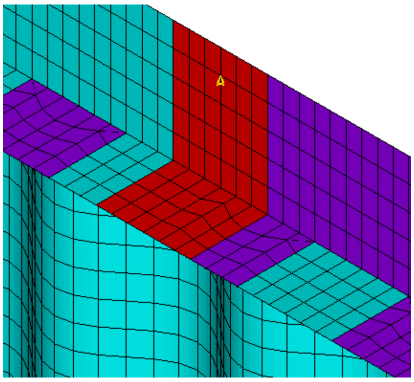


Figure 10: Displacement control loading to the shear tab

3. SIMULATION OF EXPERIMENT AND DISCUSSION

To ensure the reliability of the developed finite element model, its predictions were validated against the most comprehensive experimental study available in the literature. Reinders and Balomenos (2022) investigated the lateral–torsional buckling behaviour of sinusoidally corrugated web beams using nine specimens representing seven distinct geometric configurations. In this study, four representative beam configurations from their experimental program were selected for validation. The corresponding geometric parameters are summarized in Table 1.

Table 1: Designation of SIN Beam, (Reinders and Balomenos, 2022)

Specimen	**Web Thickness(mm)**	**Web Height(mm)**
WTA333/127x6(9)	1.897	333
WTA500/127x6	1.897	500
WTB333/127x6	2.657	333
WTC333/127x6	3.038	333

All the nine tested SIN beams have the same flange size of 127 mm width by 6 mm thickness having corrugation amplitude 20mm and sine wavelength 155mm.

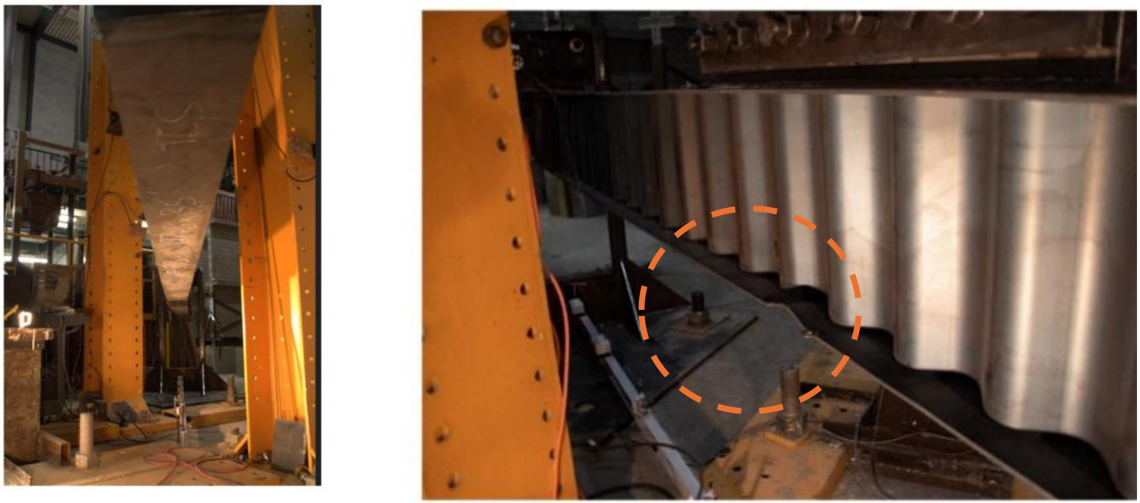
The material properties used for the FE models were defined through a bilinear kinematic hardening law, and the calibrated parameters for each case are summarized in Table 2. These parameters ensured that both elastic and inelastic responses could be captured consistently with the experimental specimens.

Table 2: Modelling parameters for verification of study of Reinders and Balomenos (2022)

Modulus of Elasticity E **(MPa)**	**Poisson's ratio** υ	**Initial Yield Stress** σ_0 **(MPa)**	**Tangent Modulus** E_T **(MPa)**
200000	0.3	408	1572

The validation focused on deformation patterns and lateral load–deflection responses, which are the most critical indicators of lateral-torsional buckling (LTB) behavior. The experimental deformed shape and the deformed pattern of the current FEM study of the specimen WTA333/127X6 (9) are presented in figures 11 and 12. The finite element analysis not only reproduced the overall lateral deflection and torsional twisting of the girder but also captured the local flange buckling observed in the experiment.

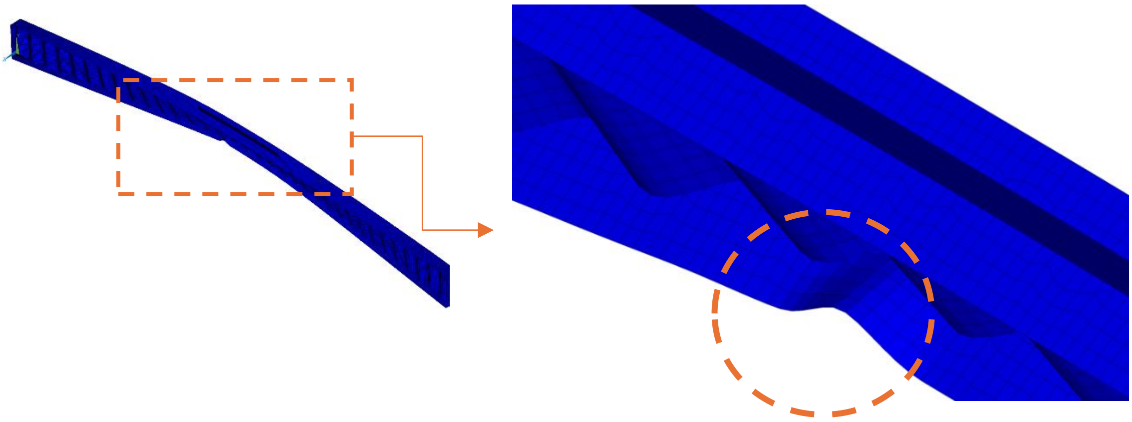
The numerical deformation pattern mirrored the onset and development of local instabilities along the compression flange with strong fidelity.



(a) Compression Flange

(b) Local Flange Buckling

Figure 11: Experimental Deformed Shape of WTA333/127X6 (Reinders and Balomenos, 2022)



Local Flange Buckling

Figure 12: Deformed Shape of the specimen WTA333/127X6 (Current FEM Study)

The experimental and FEM-generated lateral load–displacement curves for the specimens are presented in figures 13 to 16. The FEM response closely matched the experimental lateral load–deflection behavior, particularly in capturing the peak strength. Since the primary focus of this study is on lateral–torsional buckling behavior, the close agreement in lateral deflections between the FEM and experimental results confirms the validity of the numerical modeling approach. Additionally, the deformation shapes and failure patterns of all four specimens were accurately reproduced in the FEM model, demonstrating its robustness in simulating large-scale instability. This validated model is therefore considered reliable and can now be confidently used to perform an extensive parametric study aimed at understanding the influence of geometric and material parameters on the lateral–torsional buckling behavior of sinusoidally corrugated web plate girders. The outcomes from such analyses will contribute to improved design understanding, optimization potential, and future code recommendations.

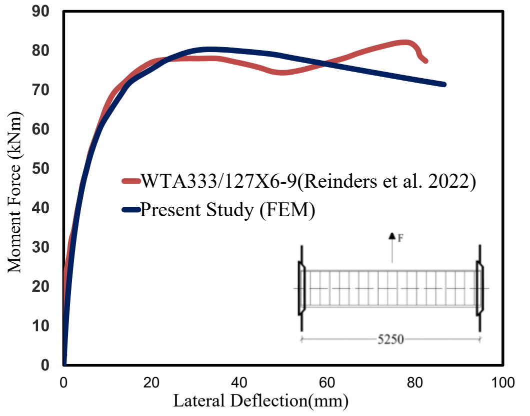


Figure 13: Comparison of Reinders and Balomenos (2022) and Simulation Results.(WTA333/127X6)

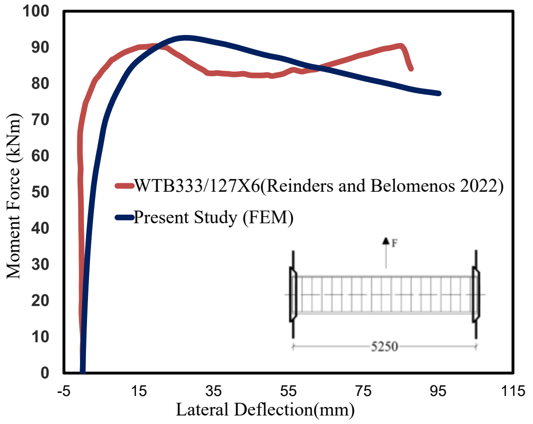


Figure 14: Comparison of Reinders and Balomenos (2022) and Simulation Results. (WTB333/127X6)

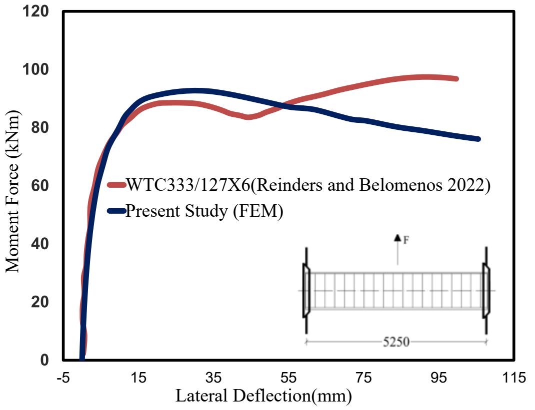


Figure 15: Comparison of Reinders and Balomenos (2022) and Simulation Results.(WTC333/127X6)

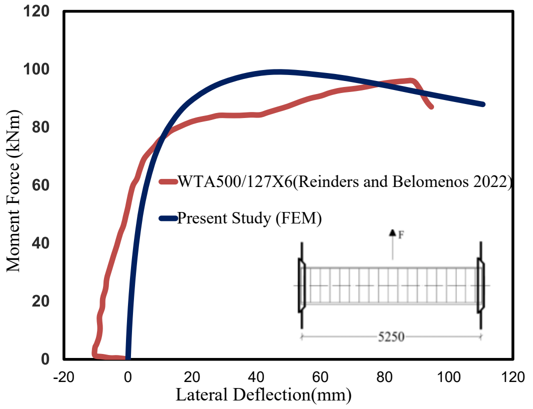


Figure 16: Comparison of Reinders and Balomenos (2022) and Simulation Results.(WTA500/127X6)

4. CONCLUSION

A three-dimensional finite element model was developed in ANSYS 19.2 to simulate the lateral–torsional buckling response of sinusoidally corrugated web plate girders, incorporating both geometric and material nonlinearities. The numerical results demonstrated strong agreement with the experimental findings of Reinders and Balomenos (2022), particularly in terms of lateral load–displacement behavior and failure mode. This close correlation validates the accuracy and reliability of the developed FE model in replicating physical behavior. Therefore, the model can be confidently used to conduct extended numerical and parametric investigations, minimizing the reliance on additional experimental testing. Overall, the findings contribute to a clearer understanding of the lateral–torsional buckling characteristics of sinusoidally corrugated web plate girders and provide a robust foundation for future research and design optimization.

DECLARATION OF USE OF AI

The authors state that the use of artificial intelligence (AI) tools was limited to language enhancement, grammar checking, and improving the manuscript's readability and clarity. The research design, data generation, numerical modeling, analysis, results interpretation, and conclusions of this study were all unaffected using AI tools. The authors, who have thoroughly examined and validated the final manuscript, are solely responsible for all technical content, modeling techniques, results, and interpretations.

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