Computational Study On Buckling Capacity Of Lipped-Channel Beams Infilled With Concrete

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Abstract
This paper presents the computational study employing finite element analysis (FEA) to evaluate the buckling capacity of lipped channel beams infilled with concrete. Locally available lipped channel sections with overall depths ranging from 100mm to 250mm were used in the computational study. The length of the beams varies between 3m and 7.5m. Two sets of beams were modeled: control beams consisting of a plain-lipped channel section and another set infilled with concrete. The analysis was conducted under two types of boundary conditions: simply supported (pinned-roller) and pinned-pinned supports. Buckling analysis was performed using LUSAS FEA under a four-point bending test. The results revealed that larger-lipped channel sections exhibited higher buckling capacities for both plain and concrete-infilled configurations. Additionally, concrete-infilled lipped channel beams with pinned-pinned support achieved greater capacities compared to their simply supported counterparts. Longer span beams, being slenderer, demonstrated reduced buckling capacities. The buckling capacity of lipped channel beams increased significantly with concrete infill compared to plain-lipped channel beams. This study highlights concrete infill as an effective method to enhance the structural capacity of open steel sections, providing a viable solution for improving their buckling performance.

Keywords: Lipped channel beam; concrete infill; finite element analysis; buckling capacity

1.0 Introduction
Steel sections are widely used in construction due to their strength and versatility. However, asymmetric single sections, such as C-sections are not widely for long-span structures because their high slenderness can lead to lateral-torsional buckling. Concrete infilled in steel beams significantly enhances structural performance by increasing stiffness and strength. This combined effect improves load-bearing capacity and delays buckling due to the increased structural stiffness provided by the concrete (Ellobody, E., & Young, B., 2006; He et al., 2024; Al-Zand et al., 2020). Studies have shown that the structural performance of steel beams can be significantly improved by adding concrete. The inclusion of concrete infill enhances the stiffness and strength of steel beams, making them more robust and rigid. This helps delay the buckling process and improves load-carrying capacity. Research on composite beams has demonstrated these advantages, with concrete infill being particularly effective in reducing distortional and localized buckling (Hélder D. Craveiro et al., 2022).

Beams are structural elements that bend or are subjected to combined shear and bending stresses. A beam's ability to withstand bending forces without failing is known as its flexural capacity. The flexural behavior of lipped channel beams are influenced by various factors, including section shape, material properties, and loading conditions. Lateral-torsional buckling can limit the flexural capacity of traditional lipped channel beams, thereby reducing their structural integrity and load-carrying capability (Sreedevi et al., 2024). Lipped channel beams are widely used in construction for their excellent load-bearing properties. Their design incorporates a flange extending from the web, improving strength and stiffness, making them ideal for various building, and infrastructure applications. Traditionally, lipped channel beams are used without infill, relying on their inherent properties to resist bending loads. However, advancements in construction techniques have prompted the use of lightweight concrete infill to enhance their flexural capacity (Borkowski et al., 2022).

Finite Element Analysis (FEA) is a powerful tool for investigating the buckling behavior of composite beams. It allows for detailed parametric studies and simulations under various loading conditions, providing insights into the complex interactions between steel and concrete (Aslani & Uy, 2015). Shashi Kant Sharma et al. (2022) found that, for every section, the global buckling failure mode of lateral-torsional buckling is characterized by a 50% contribution from torsion and 50% from bending about the minor axis. Additionally, distortion contributes to failure in the second eigenmode, while in every scenario, the mode with the lowest buckling load (i.e., the first eigenvalue) corresponds to lateral torsional buckling. Finite element studies have also examined the lateral buckling strength of a novel cold-formed steel beam (lite steel beam) when subjected to moment gradient effects. These studies revealed that lateral distortional buckling diminishes the strength benefits of the moment gradient, especially in cases with large end-moment ratios (Cyrilus Winatama Kurniawan & Mahen Mahendran, 2009; FEM Working Group, 2020; de Amorim Lana Dib & dos Santos Ramos, 2023). Thus, this paper aims to address the structural performance of lipped channel beams by examining the efficacy of concrete infill in reducing lateral torsional buckling by using finite element analysis.

2.0 Computational Study

2.1 Lipped Channels and Concrete

Locally available cold-formed lipped channel sections produced from KHP Steel Product (M) Sdn. Bhd. were used in the computational study. Figure 1 shows the cross-section of the lipped channel, and Table 1 presents the dimensions of the four lipped channels used in the study. The web dimensions are 100, 150, 200, and 250mm, while the corresponding flange sizes are 50, 65, 75, and 75mm. The lip dimensions range from 12 to 16mm, with a consistent thickness of 2.0mm.

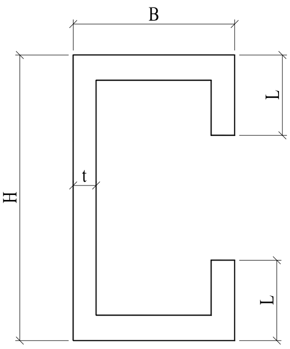


Figure 1: Typical cross-section of lipped channel

Table 1: Geometry of lipped channel section (Source: Lysaght (2020))

Channel Identification	Dimension (mm)			
	Web (H)	Flange (B)	Lip (L)	Thickness (t)
CP10020-50	100	50	12	2.0
CP15020-65	150	65	14	2.0
CP20020-75	200	75	16	2.0
CP25020-75	250	75	16	2.0

The lipped channel sections are hot-dip galvanized steel with a minimum yield stress of 450 MPa. The modulus of elasticity and Poisson's ratio are 209 GPa and 0.3, respectively. The concrete infill in the lipped channel is grade C25 having a 28 days compressive strength of 28 MPa and Poisson's ratio of 0.2.

2.2 Length and Support Condition of Lipped Channel Beams

Two sets with a total of 64 lipped channel beams were analysed. The first set is lipped channel beams without infill. The second set is lipped channel beams infilled with concrete. Four types of length ranging from 3 m to 7.5 m with an increment of 1.5 m and two types of end support conditions consist of pinned-roller and pinned-pinned were used as the parametric study.

2.3 Finite Element Analysis

2.3.1 Finite Element Modelling

A three-dimensional finite element (FE) model is used to simulate the buckling behavior of the cold-formed steel lipped channel beams. The lipped channel beams were modelled as thick shell quadrilateral elements. The quadrilateral elements (QTS4) adopt an assumed strain field for interpolation of the transverse shear strains. The inclusion of an assumed strain field prevents the element from shear locking when used as a thin shell. The displacements and rotations are considered independent and the nodal degrees of freedom. Concrete as the infill material was modelled as three-dimensional solid element. The solid element (HX8M) is based on a three-field mixed formulation in which stresses, strains and displacements are represented by three independent functions in three separate vector spaces (Frigo et al., 2020; LUSAS Team, 2022). Figure 2 shows the element of QTS4 and HX8M in LUSAS.

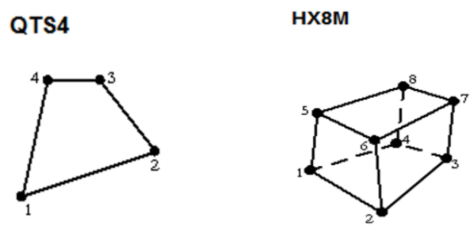


Figure 2: 3-dimensional thick shell and solid elements

2.3.2 Modelling Techniques

The FE program used is LUSAS. LUSAS is a powerful finite element analysis tool for studying the buckling behavior of steel structures. Its advanced capabilities enable the accurate modeling of thin-walled sections using shell or plate elements, effectively capturing distortional, global, and local buckling modes. LUSAS supports both linear eigenvalue and nonlinear buckling analyses, allowing for the evaluation of critical loads and post-buckling behavior. The three-dimensional FE modeling of the lipped channel beam is shown in Figure 3.

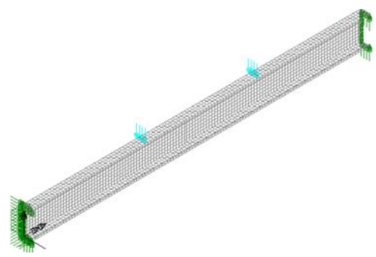


Figure 3: Three-dimensional FE model

The beams are single spans with four different spans consist of 3 m, 4.5 m, 6 m and 7.5 m. Boundary condition is applied at the whole cross section at both ends. Pinned support is assigned as displacement restraint in x, y and z directions. Meanwhile, roller support is assigned as displacement restraint in vertical (y) direction only. Lipped channel and concrete infill are meshed with thick shell elements and solid elements, respectively. The beams are applied two concentrated loads (4-point bending) vertical at the distance of L/3 and 2L/3 where L is the span as shown in Figure 4.

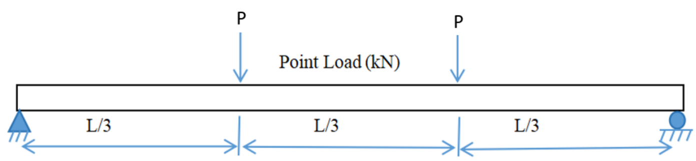


Figure 4: Loading procedure

Linear buckling analysis is used to estimate the maximum load (P) that can be supported prior to structural instability or collapse of the lipped channel beams subjected to 4-point bending. The basic assumptions of linear buckling analysis are that the linear stiffness matrix does not change prior to buckling and that the stress stiffness matrix is simply a multiple of its initial value. This technique can be used to predict the load level at which a structure becomes unstable, provided the pre buckling displacements have negligible influence on the structural response (LUSAS, 2000a). For concrete infill lipped channel beams, the contact between the steel and concrete is assumed to be fully bonded. The capacity of the beams is predicted based on the eigenvalue extraction for buckling.

2.3.3 Pre-Modelling Verification

To ensure that the method used and the FE model are appropriate, verification was performed on plain lipped channel beam using CP10020-50 by comparing the difference between the FEA results and the theoretical values based on EC3. The beam is 3 m length with the support condition of pinned-roller and subjected to 4-point bending. Based on the FEA results, the difference in buckling capacity is only 2.5% compared to the theoretical value. The failure of the beam is under buckling mode as shown in Figure 5. Therefore, it confirms that the FE method used is reliable.

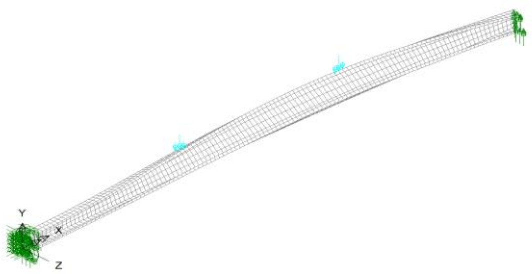


Figure 5: Failure mode of pinned-roller-lipped channel beam without concrete infill

3.0 Results and Discussion

3.1 Buckling Load

The buckling capacity of the lipped channel beam is evaluated by analyzing both global and local buckling modes. During this assessment, the beam's geometry, material properties, boundary conditions, and applied loads are carefully defined. LUSAS software was used to determine the critical buckling load, which represents the threshold at which buckling is most likely to occur. Table 2 presents the buckling capacity for pinned-roller and pinned-pinned support conditions in different sizes of lipped channel beams with varying lengths without concrete infill. The results clearly show that beams with pinned support at both ends achieve higher buckling capacities compared to beams with pinned controller support. The buckling capacity increment is ranging from 65% to 148% when both ends are pinned support.

Table 2: Buckling load of lipped channel beams without concrete infill.

Lipped Channel Section	Length of Beam (m)	Buckling Load(kN)	
		Pinned - Roller	Pinned - Pinned
CP10020-50	3	3.5	7.8
	4.5	1.2	2.7
	6	0.6	1.3
	7.5	0.4	0.8
CP15020-65	3	7.4	17.7
	4.5	3.5	6.9
	6	1.4	3.2
	7.5	0.8	1.8
CP20020-75	3	10.9	18.0
	4.5	5.0	12.1
	6	2.5	5.9
	7.5	1.4	3.2
CP25020-75	3	9.8	19.2
	4.5	5.6	11.0
	6	2.9	7.2
	7.5	1.7	4.1

Table 3 presents the buckling load of infilled lipped channel beams under different boundary conditions, specifically pinned-roller and pinned-pinned. Similar to plain lipped channel beams, all concrete infill beams with pinned-pinned support gained higher buckling load compared with pinned-roller support beams. However, the increment is not as significant compared with plain lipped channel beams. The increment is ranging from 41% to 60% when both ends are pinned support.

Table 3: Buckling load of lipped channel beams infilled with concrete.

Lipped Channel Section	Length of Beam (m)	Buckling Load (kN)	
		Pinned - Roller	Pinned - Pinned
CP10020-50	3	6.0	9.1
	4.5	2.1	3.0
	6	1.0	1.6
	7.5	0.6	0.9
CP15020-65	3	13.8	20.1
	4.5	5.4	7.9
	6	2.5	3.9
	7.5	1.4	2.2
CP20020-75	3	14.4	20.5
	4.5	9.1	14.1
	6	4.8	7.0
	7.5	2.7	3.9
CP25020-75	3	14.5	20.5
	4.5	8.1	12.5
	6	5.9	8.4
	7.5	3.3	4.9

Based on the results tabulated in Table 2 and Table 3, several findings have been found and summarised as the following.

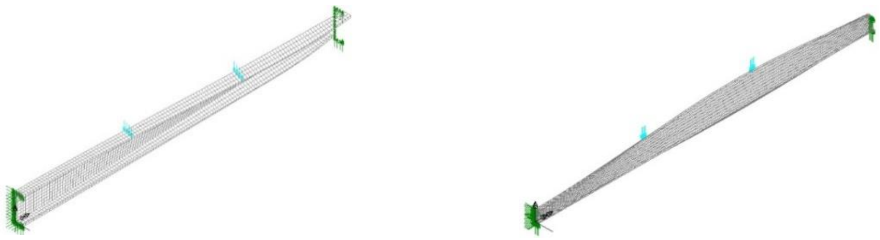
For both boundary conditions (pinned-roller and pinned-pinned) and both types of beams (plain and concrete infill), the buckling capacity for all lengths for beams using lipped channel CP15020-65 has increased significantly compared with beams using lipped channel CP10020-50. The depth of the web for CP15020-65 is 50 mm larger than CP10020-50 that significantly increase the moment of inertia in major axis. However, the increment of the buckling capacity did not show the same pattern when the depth of the web of lipped channel is further increase to 200 mm (CP20020-75) and 250 mm (CP25020-75). This phenomenon may be due to the buckling capacity is also affected by the moment of inertial in minor axis. The buckling capacity is greatly reduced when a significant portion of the smaller flange is in compression (Morkhade & Guptha, 2013). The increment of depth in lipped channel does not contribute a significant increment of moment of inertia in minor axis compared to the increment in major axis.

It has been observed that all lipped channel beams with pinned-pinned support conditions gained higher buckling load compared with beams with pinned-roller support. This finding showing that support condition is an important factor governing the buckling capacity of steel beam. In the case of pinned-roller configuration, where one end (roller) of the beam is only restraint vertically and free to rotate horizontally and out of plane, the buckling capacity experiences a notable decrease. Conversely, under the pinned-pinned condition, where both ends are restrained in all directions, there is a substantial increase in structural stability especially lateral torsional buckling leading to a remarkable enhancement in buckling capacity. This enhancement is particularly prominent in shorter lengths due to the pinned-pinned setup effectively limiting lateral displacement and augmenting load resistance.

Concrete infill has successfully enhanced the buckling capacity of lipped channel beams for both support conditions, especially pinned-roller beams. Lipped channel is an unsymmetric section when subjected to the vertical load, it will deform in the direction of load as well as it twists (lateral torsional buckling). Shear center is also known as the center of twist that affected the buckling capacity. Initially, the shear center of lipped channel is outside the web. The lipped channel with concrete infill is a composite section provides higher section properties and the shear center is shifted inside the section. Thus, lipped channel beams infilled with concrete gained higher buckling capacity.

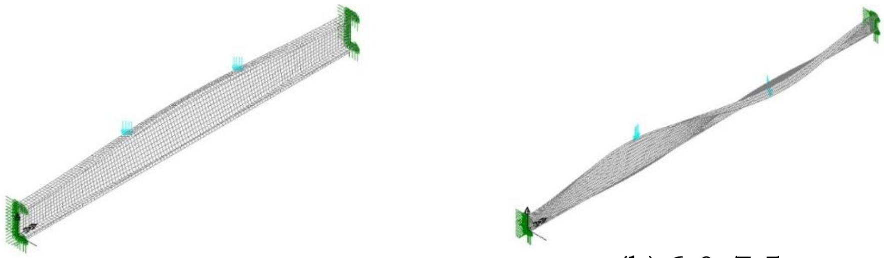
3.2 Buckling Modes

From the 64 FE models, the failure modes of the lipped channel beams due to buckling can be differentiated in terms of beam span length, boundary condition and the effect of concrete infill. Figure 6, 7, 8, and 9 summarised the buckling modes of the lipped channel beams.



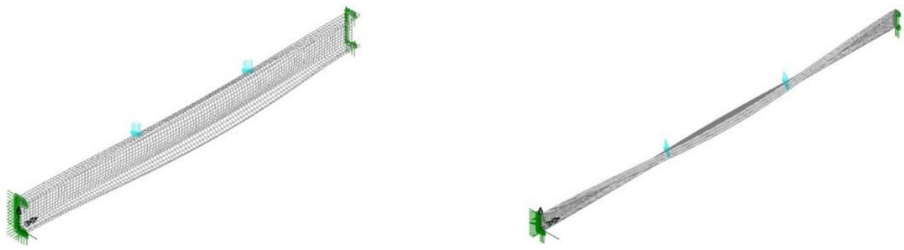
(a) 3 & 4.5 m (b) 6 & 7.5 m

Figure 6: Buckling mode of plain-lipped channel beams with pinned-roller support.



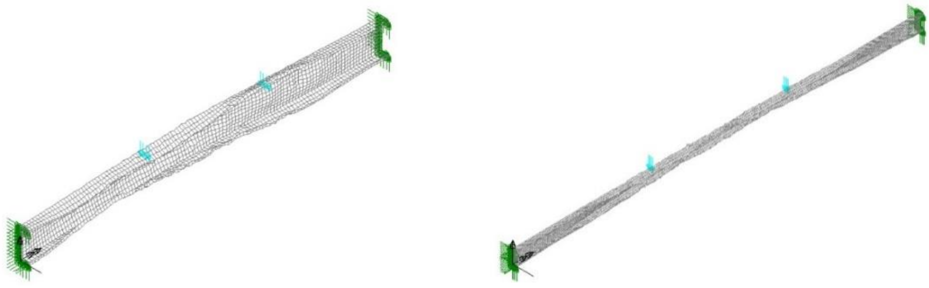
(a) 3 & 4.5 m (b) 6 & 7.5 m

Figure 7: Buckling mode of plain lipped channel beams with pinned-pinned support.



(a) 3 & 4.5 m (b) 6 & 7.5 m

Figure 8: Buckling mode of concrete infill lipped channel beams with pinned-roller support.



(a) 3 & 4.5 m (b) 6 & 7.5 m

Figure 9: Buckling mode of concrete infill lipped channel beams with pinned-pinned support.

For short-lipped channel beams (Figure 6a) without concrete infill, twisting has happened at the roller support with some lateral torsional buckling between the two concentrated loads. However, for long-lipped channel beams (Figure 6b) twisting is likely to happen between the two concentrated loads. When both supports are pinned, the short-lipped channel beam (Figure 7a) without concrete infill buckles in one side between the two concentrated loads. Meanwhile, the long-lipped channel beam (Figure 7b) is subjected to twisting in double curvature.

Concrete infill enhanced the buckling capacity of lipped channel beams. The buckling modes for concrete infill lipped channel beams with pinned-roller support (Figure 8), the buckling modes are almost similar to plain lipped channel beams with pinned-pinned support. Lipped channel beams infilled with concrete and with pinned-pinned support (Figure 9) achieved the highest capacity. The failure modes are very much different compared with other beams. These beams are subjected to local failure especially between the two concentrated loads. Global bucking is not significant found in these beams where the web and flange of the lipped channel are subjected to local buckling and crushing.

4.0 Conclusions

The effect of concrete infill and support condition on the buckling behavior of lipped channel beams subjected to concentrated load has been investigated through the finite element analysis. Pinned-pinned support condition has significant contribution in enhancing buckling capacity of lipped channel beams without concrete infill reaches a capacity increase of more than 100%. Concrete infill has successfully increased the buckling capacities of lipped channel beams. The effect of concrete infill shows very encouraging results for beams with pinned-roller support. The buckling mode of lipped channel beams performs differences due to changes in beam length, boundary conditions and caused by concrete infill. Generally, two types of buckling modes have been identified where lipped channel beams without concrete infill experience global buckling and lipped channel beams with concrete infill subjected to local failure. Long span lipped channel beams without concrete infill show the twisting between the two concentrated loads. Concrete infill has successfully increased the capacity of lipped channel beams, allowing them to be used for longer structures and carry higher loads.

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Author Contributions

The author's contributions to this manuscript are as follows:
T. J., Chai: Conceptualization, Methodology, Software, Original Manuscript Draft Preparation; **Fauziah, A:** Software, Manuscript Improvement: **H. B., Koh:** Software, Validation, Manuscript Reviewing and Editing.

Conflicts Of Interest

This manuscript has not been published elsewhere and is not under consideration by other journals. All authors have approved the review, agree with its Submission, and declare no conflict of interest in the manuscript.

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