Compression Resistance of High-Density Polyurethane Foam-Filled Light-Gauge Steel Tubes: An Empirical Model

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**Abstract.** Composite elements have proven efficient in structural applications due to the combined properties of different materials. Recently, high-density polyurethane (PU) foam-filled light gauge (LG) square tubes have emerged as a significant advancement in composite systems. These tubes offer an improved strength-to-weight ratio and provide an economical and sustainable solution for lightweight structural applications, including seismic elements, due to their adequate energy absorption capabilities. Although the structural performance of high-density PU foam-filled LG steel tubes under compression has been demonstrated, a lack of design provisions specifically for PU foam as an infill material globally exists. This study aims to bridge this limitation by evaluating the compatibility of existing concrete-filled tube (CFT) design provisions with experimental results for high-density PU foam-filled LG steel tubes. An empirical model is subsequently developed using multi-nonlinear regression analysis. The results indicate that the width-to-thickness (B/t) ratio and the length-to-width (L/B) ratio play crucial roles in determining compressive resistance, thereby impacting local and global buckling due to geometric instability. This study highlights the importance of both geometric and material parameters in governing compressive resistance and provides design recommendations for construction practices.

**Keywords:** High-density PU foam-filled LG steel tubes, Compressive Resistance, Analytical Model, Empirical Model, Multi-nonlinear-regression analysis

1. Introduction

High-density PU foam-filled LG steel tubes showcase as a better alternative to CFT systems for lightweight constructions, including crash barriers and seismic resistant elements concerning its strength-to-weight ratios and sustainability. This new approach to composite systems has been evolving recently in the global industry for its efficiency as an effective structural element. The literature and experimental investigations by Padmaja et al. [1] show that the strength enhancement of empty tubes to high-density foam-filled tubes is based on increased energy absorption. The failure behavior of foam-filled tubes changes from collapse mode to diamond and concertina modes with increasing D/t ratio and foam density. The high-density PU foam-filled aluminum and LG square tubes yielded higher strength than the superimposed strengths of foam and tube, attributing to the significant composite mechanism and bond capacities [2]. A similar enhancement due to interaction effects was also observed for foam-filled aluminum square tubes [3]. The strength is enhanced from empty tubes to high-density PU foam-filled tubes by reducing folds in the metal envelope due to the stabilization effect of the infill material indicating geometric stabilities by resisting local buckling effects of thin wall sections. This composite system also exhibits significant performance in flexural as the PU foam infill controls the local buckling effects and allows the yielding of material up to the plastic limit [4]. The stresses are redistributed from the fold under loading and form an adjacent fold, the mechanism enhanced flexural strength by 60% compared to empty tubes failing by localized buckling under loading. The above studies [1-2, 4] concluded that the High density (150 kg/cum) PU foam-filled LG steel square tubes are compatible with equivalent M14 concrete-filled tubes. Also, the finite element analysis (FEA) results for compression and flexural agreed with the experimental results. Thus, FEA is suggested for future evaluations over expensive experimental tests. Reid et al. [5] conducted experimental tests and found that thin-walled empty tubes exhibited an asymmetric deformation pattern, whereas foam-filled tubes showed a more symmetric deformation. Seitzberger et al. [6] found that the influence of global bending on foam-filled circular steel tubes under axial compression was reduced compared to that on empty tubes owing to composite action.

In summary, the high-density PU foam is better suited for structural engineering applications concerning its high energy absorptions. Followed by, high-density PU foam-filled tubes with geometric stability. Considering its sustainability, efficient performance in compression, and limited design provisions, the present study aims to compare the existing analytical models with the experimental results of high-density PU foam-filled LG steel tubes and develop an empirical model through multi-nonlinear regression analysis. This study provides insights into the appropriate parameters governing compressive strength and recommends optimal design guidelines.

1. Experimental Investigations

The experimental investigation was carried out in past research [2], for the quasi-static compression strength of High-density PU foam-filled LG tubes. The enhancements of foam-filled LG steel square tubes' compressive strength from the superimposed strength of PU foam and LG steel tubes are listed in Table 1. Their investigations not only highlight the enhanced structural response due to adequate composite action between LG steel envelope and High-density PU foam but also showcase material optimization as the enhancements are greater when L/B and B/t ratios are higher attributing the optimal use of high-density PU foam for thin-walled tube resisting local buckling issues.

**Table 1.** Mean crushing strength

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| B/t | L/B | Mean Compressive Strength (kN) | | | | Enhancement (%) |
| Foam | Tube | Foam + Tube | Foam Filled Tube |
| 83.33 | 2 | 2.58 | 36.37 | 38.95 | 54.51 | 39.95 |
| 83.33 | 3 | 2.58 | 39.50 | 42.08 | 61.45 | 46.03 |
| 83.33 | 4 | 2.58 | 39.88 | 42.46 | 71.68 | 68.82 |
| 100 | 2 | 2.58 | 29.92 | 32.49 | 44.05 | 35.58 |
| 100 | 3 | 2.58 | 34.60 | 37.18 | 48.58 | 30.66 |
| 100 | 4 | 2.58 | 35.00 | 37.58 | 49.04 | 30.49 |
| 125 | 2 | 2.58 | 19.29 | 21.87 | 32.80 | 49.98 |
| 125 | 3 | 2.58 | 18.67 | 21.25 | 33.53 | 57.79 |
| 125 | 4 | 2.58 | 23.28 | 25.86 | 45.87 | 77.38 |

Through the conducted experiments, the ultimate compressive strength was also ascertained, and the results are summarized in **Table 2**.

**Table 2.** Ultimate compressive strength

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| B/t | L/B | Ultimate Compressive Strength (kN) | | | | Enhancement (%) |
| Foam | Tube | Foam + Tube | Foam Filled Tube |
| 83.33 | 2 | 13 | 71 | 84 | 98 | 16.67 |
| 83.33 | 3 | 13 | 73 | 86 | 109 | 26.74 |
| 83.33 | 4 | 13 | 68 | 81 | 134 | 65.43 |
| 100 | 2 | 13 | 68 | 81 | 87 | 7.41 |
| 100 | 3 | 13 | 68 | 81 | 90 | 11.11 |
| 100 | 4 | 13 | 61 | 74 | 93 | 25.68 |
| 125 | 2 | 13 | 41 | 54 | 66 | 22.22 |
| 125 | 3 | 13 | 43 | 56 | 66 | 17.86 |
| 125 | 4 | 13 | 43 | 56 | 70 | 25.00 |

The observed enhancement in both the mean crushing strength and ultimate compressive strength of LG steel tubes infilled with high-density PU foam highlights significant composite action, particularly in terms of bond capacity and energy absorption. The structural behavior and performance were primarily influenced by local buckling of the thin-walled sections rather than global buckling, reflecting the classification of these test specimens as short columns.

Failure modes were validated using finite element analysis (FEA) with a dynamic explicit approach in Abaqus software, as detailed in Table 3, which reveals that these short columns exhibit local buckling in the thin-walled metal envelopes. Empty tubes showed extensive local buckling at alternate faces along their entire length, while tubes filled with high-density PU foam exhibited progressive folding, initiating at the contact surface under load application, with the lower sections remaining stable. The high-density PU foam provides lateral triaxial confinement to the metal envelope, enhancing the load-carrying capacity through its composite action without causing microcracking. However, the bond between the infill and the envelope is crucial for compressive resistance. The FEA results further corroborate these findings by highlighting stress concentrations indicative of local buckling, where the thin walls undergo plastification and localized buckling (refer to Table 3).

**Table 3.** Failure mode shapes for specimens with a B/t ratio of 100.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| L/B | Empty Tubes | | High-Density PU Foam Filled Tubes | | |
| Experimental | FEA | | Experimental | FEA |
| 2 | C:\Users\gpadmaja\Desktop\Technical\PhD-Final-8-11-19\PADMAJA Lab data\Final Experimental Results\GI tube testing\Empty Tube\COMPRESSION\Pictures\Photos\IMG_20180523_124806.jpg |  | | **C:\Users\gpadmaja\Desktop\Technical\PhD-Final-8-11-19\PADMAJA Lab data\Final Experimental Results\GI tube testing\Foam Filled\COMPRESSION\Pictures\Photos\Picture-2.jpg** | Stress_Abq.JPG |
| 3 |  |  | | **C:\Users\gpadmaja\Desktop\Technical\PhD-Final-8-11-19\PADMAJA Lab data\Final Experimental Results\GI tube testing\Foam Filled\COMPRESSION\Pictures\Photos\Picture-2.jpg** | Stress.JPG |
| 4 | C:\Users\gpadmaja\Desktop\Technical\PhD-Final-8-11-19\PADMAJA Lab data\Final Experimental Results\GI tube testing\Empty Tube\COMPRESSION\Pictures\Photos\picture-41.jpg |  | |  | Stress.JPG |

1. Analytical Models

The quasi-static compression results for high-density PU foam-filled LG steel square tubes from experimental investigations [2] were compared with analytical models from the relevant literature, utilizing the same material and geometric properties mentioned in Table 4 and Table **5**, respectively. The study aimed to identify a compatible analytical model for predicting compressive resistance for design practices.

**Table 4.** Material properties

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Material | Density | Yield Strength | Ultimate Strength | Elasticity Modulus | Poisson’s ratio | Elongation |
|  | (kg/m3) | (MPa) | (MPa) | (MPa) |  | (%) |
| LG Steel | 7850 | 345 | 450 | 200000 | 0.3 | 12 |
| PU Foam (T) | 150 | 1.587 | 1.80 | 158.5 | 0.33 | 8 |
| PU Foam (C) | 150 | 5.20 | 14.03 | 226 | 0.33 | NA |

Note. T: Tension, C: Compression.

**Table 5.** Geometric properties

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Length (L mm) | Thickness (t mm) | Width (B mm) | B/t | L/B |
| 200 | 1.2 | 100.0 | 83.33 | 2 |
| 300 | 1.2 | 100.0 | 83.33 | 3 |
| 400 | 1.2 | 100.0 | 83.33 | 4 |
| 200 | 1.0 | 100.0 | 100 | 2 |
| 300 | 1.0 | 100.0 | 100 | 3 |
| 400 | 1.0 | 100.0 | 100 | 4 |
| 200 | 0.8 | 100.0 | 125 | 2 |
| 300 | 0.8 | 100.0 | 125 | 3 |
| 400 | 0.8 | 100.0 | 125 | 4 |

* 1. LG Steel Empty Square Tube

Abramowitz and Jones [7] developed a theoretical equation for predicting the crushing strength of square tubes in terms of the plastic flexural capacity and the cross-sectional aspect ratio contributing to local buckling effects. Further, the study was expanded over a large series of experimental investigations, and a theoretical equation was proposed with respect to failure mode shapes considering symmetric, asymmetric, and extensional collapse modes [8]. Magee and Thornton’s [9] analytical model predicts the mean compressive strength based on the material’s maximum tensile capacity and relative density. However, the literature proposed analytical equations were used to compute the mean crushing strength () of the present study’s experimental specimens, as presented in Table 6.

**Table 6.** Analytical models for empty tubes

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Model | Equation | Mean Crushing Strength (kN) | | |
| B/t: 125 | B/t: 100 | B/t: 83.33 |
| Abramowicz & Jones [7] |  | 12.98 | 18.84 | 25.55 |
| Abramowicz & Jones [8] |  | **20.33** | **28.93** | **38.64** |
| Magee [9] |  | 25.82 | 36.17 | 47.66 |

In the above analytical models, is the plastic bending moment, which is computed using Eq. 1.

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Where refers to the flow stress, and it aligns between the yield stress ( and ultimate tensile strength (, as shown in Eq. 2.

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By comparing experimental results with theoretically evaluated mean compressive strengths, Abramowicz & Jones's [8] model showcases fair agreement despite deviations. However, the plastic bending moment is with respect to the flow stress, which is considered as the average of elastic bending moment concerning yield stress and the collapse plastic bending moment concerning the ultimate tensile stress. Which indicates the flexural capacity at an elastoplastic state but does not signify the full plastic flexural capacity. Even though the models are for short columns, the minimal effect of global buckling concerning unsupported length is not considered. Therefore, it is recommended to incorporate length variations and generalized plastic bending moment.

* 1. High Density PU Foam Filled LG Steel Square Tube

Analytical models for high-density PU foam-filled LG steel square tubes are absent; hence, the analytical models proposed in pertinent literature and International standards for concrete-filled tubes (CFT) are studied to understand the influencing parameters for the formulation of empirical equations.

IS: 11384-2022 [10], the design compressive resistance () of short composite columns was determined by considering elastic buckling phenomena. For circular tubes (refer to Eq. 3), geometric instabilities and bonding action are included. The global and local buckling effects are influenced by the slenderness ratio and thickness to its diameter, respectively. The interfacial interactions are governed by the modular ratio of the materials used. In contrast, for square tubes (refer to Eq. 4), local and global buckling effects are typically not considered, focusing instead on material properties.

(3)

(4)

Where, and ​ represent the cross-sectional areas of the steel envelope and infill concrete, respectively. is the yield stress of the steel, while ​ denotes the concrete’s characteristic compressive strength. and ​ are partial safety factors, and is the normalized slenderness ratio, which accounts for Euler’s elastic buckling load.

The design compressive resistance expression for circular tubes can be effectively represented by three key components: (i) the peak strength derived from the steel tube, accounting for material yielding, which is adjusted for geometric instability due to global buckling; (ii) 80% of the infill concrete’s strength, considering long-term durability effects; and (iii) the load transfer from the steel tube to the concrete infill, which is proportioned based on the infill area, taking into account both local buckling effects (t/d) and global buckling effects (λ). This formulation is also applicable to and recommended for square tubes.

The Indian standard guidelines are a modified version of the Euro standard [11] concerning Indian conditions and scenarios. Although these standards incorporate geometric instabilities over length concerning the global buckling criteria over British Standard [12].

**Table 7.** Mean crushing strength of PU foam-filled LG steel square tubes

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| B/t | L/B | Ultimate Compressive Strength (kN) | | |
| Square [10] | Equivalent Circular [10] | Experimental |
| 83.33 | 2 | 219.86 | 256.08 | 98 |
| 83.33 | 3 | 219.86 | 243.77 | 109 |
| 83.33 | 4 | 219.86 | 233.00 | 134 |
| 100 | 2 | 195.91 | 225.60 | 87 |
| 100 | 3 | 195.91 | 214.97 | 90 |
| 100 | 4 | 195.91 | 205.74 | 93 |
| 125 | 2 | 171.86 | 194.90 | 66 |
| 125 | 3 | 171.86 | 186.01 | 66 |
| 125 | 4 | 171.86 | 178.39 | 70 |

The Indian standard provisions for both circular and square tubes were employed to compute the design compressive strength of the specimens used in the experimental investigations, as shown in Table 7. The results of the experiment and the design strength comparison show that both expressions tend to overestimate strength because they do not adequately account for bond interactions and geometric instability. The expression for circular tubes shows variation with length, but the square tube expression doesn’t carry with respect to length. The design practices for polyurethane foam-filled LG steel tubes utilizing these provisions are unsafe and highlight the requirement for new design provisions.

1. Empirical Modelling

The above analytical models showcase the limitation in predicting the compressive strength of LG steel tubes considering global buckling effects and plastic flexural capacities, and less compatibility in predicting the ultimate compressive strength of High-density PU foam-filled LG steel tubes utilizing equivalent CFT analytical models. The present study aims to develop an empirical model based on the experimental results using a machine learning algorithm. Although there is an absence of machine learning models for high-density PU foam-filled tubes, a literature survey was carried out on empirical models of CFT to understand the efficiency of machine learning algorithms for composite systems.

Kaveh et al. [13] predicted the maximum buckling load of composite cylinders with varying stiffness by employing various machine learning algorithms and found reasonable accuracy with multiple linear regression, although deep learning models are highly accurate but with larger datasets. In comparison with conventional design codes, Naser et al. [14] achieved improved accuracy in predicting the structural response of CFT columns with the application of machine learning. The literature referred to underscores the efficacy of machine learning approaches in modelling nonlinear engineering problems, particularly highlighting the efficiency of composite system applications.

* 1. Framework for Empirical Modelling

The framework for developing an empirical model through machine learning algorithms such as multi-nonlinear regression analysis is illustrated in **Fig. 1**.



**Fig. 1.** Framework for developing an empirical model.

The data for developing the empirical model is acquired from experimental tests and subsequently pre-processed to meet the model’s requirements. The governing parameters are determined through Pearson correlation analysis and by referencing past analytical models to formulate a preliminary empirical equation. The dataset is then divided into training, validation, and testing subsets based on the data's quality and quantity. Validation is required for tuning hyperparameters and selecting only the most influential independent parameters.

The preliminary equation, with arbitrary coefficients, is analysed using a nonlinear regression approach. The performance of the developed model, with its determined coefficients, is evaluated using statistical indices. Given that the model’s performance depends heavily on the quality of the data in the respective subsets, it is recommended to perform cross-fold validation, contingent upon the database’s quantity.

If the empirical model’s performance does not meet the desired statistical indices, the preliminary equation is modified by adjusting the formulations and independent parameters until satisfactory performance is achieved.

Regression analysis was performed in this study using MATLAB (version R24a, 2024) to develop an empirical model that predicts the compressive resistance of light-gauge steel square tubes filled with high-density PU foam. Although the data points are limited, this pioneering research establishes design guidelines for construction practices using training datasets only. The performance of the empirical models was assessed using the coefficient of determination (R²) as a statistical indicator (see Eq. 5). The R² value is calculated as follows:

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Where n denotes the number of data points,​: the dependent variable's actual values, : the dependent variable's predicted values, and, ​: the dependent variable's mean.

The empirical modelling is conducted with the following assumptions: (i) The empirical expressions are applicable only to short columns, with an L/B ratio ranging from 1 to 5 and a B/t ratio between 80 and 130. (ii) Eccentricity effects are neglected in accordance with short column theory. (iii) The local and global buckling criteria are indirectly considered using the B/t and L/B ratios, respectively. (iv) The effective length is taken as the actual length for adopting a conservative approach.

* 1. Correlation Analysis

A correlation analysis was performed using the raw data provided in Table 1. Mean crushing strengthobtained from the experimental investigations (refer to Section 2) for both empty and high-density PU foam-filled LG steel square tubes. The resulting correlation matrix, depicted in Fig. 2, demonstrates that the local buckling parameter (B/t) has a more pronounced influence on compressive resistance compared to the global buckling parameter (L/B).



**Fig. 2.** Correlation matrix of empty and high-density PU foam-filled LG steel tubes

However, the L/B ratio also significantly affects compressive resistance, suggesting that both the D/t and L/D ratios should be incorporated into machine learning models to account for geometric instability due to global and local buckling, respectively.

The analysis reveals that the influence of the local buckling parameter is lowered in foam-filled tubes than in empty tubes, whereas the impact of the global buckling parameter increases. This observation is consistent with experimental findings, which show that foam infill mitigates localized buckling in tubes with thin walls, leading to the formation of progressive folds associated with global buckling. Additionally, it can be observed that within the range of tested specimens, compressive resistance exhibits a negative relationship with the B/t ratio; thus, load-carrying capacity decreases with an increase in the B/t ratio, indicating that thinner sections are more susceptible to buckling. In contrast, the L/B ratio exhibited a positive relationship with compressive strength.

* 1. Empirical Model of Empty LG Steel Square Tubes

The empirical model was developed for determining the mean crushing strength of LG steel tubes based on the experimental dataset, following the nearby theoretical formulations of Abramowitz and Jones [8], which addresses the limitations of global buckling effects and elastoplastic flexural capacity.



**Fig. 3.** Mean crushing strength of LG tubes, w.r.t (a) B/t and (b) L/B ratios.

The mean crushing strength’s variation with respect to width-to-thickness ratio and length-to-width ratio is illustrated in Fig. 3, which account for local and global buckling effects due to geometric instabilities, respectively. The compressive resistance drastically drops for the B/t ratio due to the local buckling of the thin wall. In addition, the compressive resistance showcases nearly linear variation with respect to the L/B ratio, significantly for the B/t ratio of 125, suggesting consideration of global buckling effects in short columns that align with correlations.

Therefore, In the present empirical model, the elastoplastic flexural capacity is replaced by the plastic flexural capacity (considering plastic section modulus ( and yield stress of the material () and the global buckling effects are considered by introducing a length to width ratio in the formulation.

(6)

(7)

(8)

Where regression coefficients, are 18.785, 0.220, -4.279 respectively. are -0.0027 and -0.0022, respectively.

The compressive strength varies quadratically with respect to the B/t ratio; however, the variation with respect to the L/B ratio can be approximated to be linear. Further, the plastic flexural capacity was adjusted by the bucking factors, considering the above variation types, to predict compressive strength with a performance index R2 of 0.968.

* 1. Empirical Model of PU Foam-Filled LG Steel Square Tubes

The variation in the ultimate compressive strength concerning the local buckling parameter (B/t) and the global buckling parameter (L/B), is depicted, respectively, in Fig. 4. It is evident that both buckling criteria have a noteworthy effect on compressive capacity. Notably, when the B/t ratio exceeds 100, the influence of local buckling becomes consistent across all lengths because the compressive strength for all L/B ratios converges beyond this threshold.



**Fig. 4.** Compressive strength of PU foam-filled LG steel tubes, (a) B/t and (b) L/B ratios.

The use of CFT analytical models for the design of high-density PU foam-filled LG steel square tubes is the least compatible, which results in unconservative practice. Therefore, the Indian standard guidelines for estimating the compressive strength of circular CFTs were modified for LG steel tubes filled with PU foam of high density based on the present experimental results, as it considers geometric instabilities and bond interactions.

(9)

Where, and ​ represents the cross-sectional area of foam infill and ultimate compressive strength of high-density PU foam, respectively. And regression constants, are 9.664, -10.839, -41.090, and 44.956, respectively. The developed empirical expression demonstrates satisfactory performance with a coefficient of determination index of 0.955.

1. Comparative Analysis

A comparative analysis was carried out for various D/t and L/D ratios considering the mean cursing strength of the empty LG square tubes and the ultimate compressive strength with high-density PU foam infilling. These comparisons are presented in Fig. 5 and Fig. 6 respectively, considering experimental results, the nearby analytical model, and the developed empirical model.

**Fig. 5.** Comparative plot for empty tubes

**Fig. 6.** Comparative plot for foam-filled tubes

The comparative analysis indicates that the empirical model provides accurate predictions when accounting for length variation and effectively incorporating global buckling criteria. However, the predicted values vary up to 10% with experimental results, so the partial safety factors can be utilized for conservative design practice concerning safety.

1. Conclusions

The following findings are presented as the conclusions of this study:

1. The infill of high-density (150 kg/m³) PU foam in light-gauge (LG) steel tubes significantly enhances composite strength, particularly for thinner walls and longer lengths. This demonstrates the foam’s effectiveness in optimizing the structural behavior of tubes that are highly prone to local and global buckling effects.
2. Empty LG steel tubes experience local buckling, manifesting as folds along alternate faces throughout the length. In contrast, high-density foam-filled tubes also fail due to local buckling, but exhibit progressive folding with reduced depth. This transition in failure mode from empty to foam-filled tubes indicates improved geometrical stability due to the infill, which helps to resist buckling.
3. The Abramowicz & Jones [8] model was found suitable for predicting the compressive strength of empty LG steel tubes. However, it tends to underestimate strength depending on the B/t ratio, without accounting for variations in length. The results suggest modifications that better incorporate global buckling effects and the full plastic bending capacity.
4. The Indian Standard [10] provisions for concrete-filled tubes (CFT) in square sections do not account for geometrical instabilities, while for circular sections, both buckling effects and interaction effects are considered. However, these provisions significantly overestimate the compressive resistance of high-density foam-filled LG steel square tubes, highlighting the need for future design guidelines to address this discrepancy.
5. Correlation analysis comparing empty and foam-filled tubes revealed a reduced influence of the local buckling parameter (D/t) on compressive resistance and a positive influence of the global buckling parameter (L/B) across the specimen range. These findings align with experimental investigations and FEA visualizations. However, the correlations indicate that the B/t parameter primarily governs the compressive strength, whereas L/B also plays a significant role.
6. For foam-filled tubes, when the B/t ratio exceeded 100, the influence of local buckling became consistent across all lengths, as the compressive strength for all L/B ratios converged beyond this threshold.
7. The empirical models developed for both empty and foam-filled tubes address the limitations of neglecting length variations and global buckling influence by incorporating global buckling criteria through the L/B ratio. These models demonstrate reasonable accuracy for different lengths.

In summary, high-density PU foam as an infill material provides adequate geometric stability for LG steel tubes without microcracking. The composite action through triaxial confinement is particularly significant for thinner wall sections and longer lengths, indicating its efficiency in resisting both local and global buckling effects. Existing equivalent analytical models for empty and foam-filled tubes ignore length variations and are found to be unconservative for design practices. Despite the limited data available, this study pioneers design provisions for high-density PU foam-filled LG steel square tubes and recommends, an empirical model that predicts compressive strength by incorporating global buckling effects through the L/B ratio. These preliminary models can be further refined using larger datasets for PU foam-filled tubes.

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