Predicting Compressive Strength of High-Density PU Foam-Filled Aluminum Tubes Using Machine Learning Algorithms

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**Abstract.** High-density polyurethane (PU) foam-filled aluminum tubes represent a significant advancement in composite systems, boasting an exceptional strength-to-weight ratio and sustainability. These materials offer an economical solution for lightweight structural applications, including seismic braces, due to their effective energy absorption capacities. Despite the demonstrated performance of high-density PU foam-filled aluminum tubes in compression and their adequate bonding capacities, there is a notable absence of analytical and empirical models specifically for PU foam as an infill material. This study aims to address this gap by comparing existing concrete-filled tube (CFT) analytical models with experimental results and developing an empirical model using machine learning algorithms for aluminum tubes filled with high-density PU foam. The findings reveal that the diameter-to-thickness (D/t) ratio and the length-to-diameter (L/D) ratio significantly influence compressive resistance, affecting local and global buckling, respectively. Additionally, the material strength and geometric area of both the infill material and the metal envelope are critical factors. The study offers valuable insights into the parameters that govern compressive strength, providing recommendations for futuristic optimal design approaches.

**Keywords:** High-density PU foam-filled aluminum tubes, Compressive Strength, Analytical Model, Empirical Model, Machine Learning Algorithms

1. Introduction

Concrete-filled steel tubes (CFSTs) are extensively recognized for their structural efficiency, driven by their composite behavior and effective load transfer mechanisms that benefit from triaxial confinement. However, the growing demand for lightweight and cost-effective construction solutions has shifted attention towards alternative materials such as high-density polyurethane (PU) foam-filled aluminum tubes. These composites offer promising advantages for applications like crash barriers and lightweight structures considering their favorable strength-to-weight ratios, resistance to corrosion, and superior stiffness while mitigating torsional effects. High-density PU foam, as a sustainable infill, enhances energy absorption and structural bonding, making it a valuable component in modern construction practices.

The literature reveals significant insights into the structural functionality of composite tubes, particularly focusing on high-density PU foam. Onsalung et al. [1] examined the foam density impact on the specific energy absorption of foam-filled steel tubes under axial crushing. Their findings indicate that higher foam densities increase the number of folds and energy absorption, with 150-200 kg/m³ foam providing an optimal performance concerning structural weight and energy absorption. Onsalung et al. [2] further explored the impact behaviour of polyurethane foam-filled circular aluminum tubes, demonstrating that foam-filling transitions, and collapse modes from asymmetric to axisymmetric and enhance energy absorption. Thinvongpituk et al. [3] investigated the crush characteristics of PU foam-filled circular steel and aluminum tubes under quasi-static compression loading, revealing that foam filling alters collapse modes and enhances energy absorption, although specific energy absorption may decrease with increasing foam density.

Padmaja et al. [4] Compared various infill materials as alternatives to concrete in composite-filled tubes. As per their study, High-Density PU foam (150kg/m3) filled aluminium tubes demonstrated significant composite behaviour with considerable strength-to-weight ratio. Further research by Padmaja et al. [5] on the quasi-static axial compression behavior of high-density PU foam-filled aluminum tubes with various D/t and L/D ratios, confirmed enhanced local buckling resistance and load-carrying capacity due to composite action. Their finite element analysis supported these experimental results, emphasizing the potential of foam-filled tubes for lightweight structural applications. The study validated that the compressive strength of foam-filled tubes outperforms the superimposition of empty tubes and foam alone, especially at lower B/t ratios. Mantena et al. [6] also investigated the flexural performance of light gauge steel tubes filled with high-density PU foam, revealing a significant 60% improvement in flexural strength compared to empty tubes. This research underscored the enhanced strength-to-weight ratios and reduced local buckling, recommending high-density PU foam as infill material in composite-filled tubes for structural applications.

The reviewed literature underscores the structural efficiency and performance of high-density PU foam-filled aluminum tubes, highlighting their advantages in energy absorption, load-carrying capacity, and overall structural behavior. Despite these advancements, empirical models for compressive strength and performance optimization of these composites remain limited. This study aims to address this gap by comparing existing analytical models with experimental results and developing an empirical model using machine learning algorithms. The objective is to provide insights into the parameters influencing compressive strength and recommend futuristic optimal design approaches for high-density (150 kg/cum) PU foam-filled aluminum tubes. This research will contribute to enhancing the application and design calculations of these innovative composites in modern construction practices.

1. Axial Compression of Empty and High-Density PU Foam-Filled Aluminum Circular Tubes.

The experimental and numerical investigations performed by Padmaja et al. [4–5] demonstrated the greater compatibility of aluminum with high-density PU foam due to its bonding capabilities concerning an equal poison ratio. Their study also showcased that finite element analysis yields reasonable accuracy in comparison with experimental results, suggesting an alternative to the expensive experimental testing process. Similarly, the tests are also performed for specimens with an L/D ratio of 4.98 and a D/t ratio of 40.20 and 30.15, in the present study. By aiming to observe the variations in compressive resistance due to longitudinal and cross-sectional effects concerning global and local buckling, the findings are illustrated in **Table 1**.

**Table 1.** Mean crushing strength of high-density PU foam-filled aluminum tubes [5].

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| D/t | L/D | Mean Crushing Strength (kN) | | | | Enhancement (%) |
| Foam | Empty | Foam + empty | Foam filled |
| 40.20 | 3.32 | 2.58 | 28.27 | 30.85 | 46.77 | 51.60 |
| 30.15 | 3.32 | 2.58 | 39.88 | 42.46 | 49.10 | 15.64 |
| 40.20 | 4.98 | 2.58 | 26.86 | 29.44 | 45.37 | 54.11 |
| 30.15 | 4.98 | 2.58 | 37.89 | 40.47 | 47.63 | 17.69 |

**Table 2.** Buckling modes of high-density PU foam-filled aluminum tubes (L/D of 3.32) [4].

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| D/t | Empty tubes | | Foam filled tubes | |
| Exp. | FEA | Exp. | FEA |
| 30.15 | C:\Users\gpadmaja\Desktop\Technical\PhD-Final-8-11-19\PADMAJA Lab data\Al Tube Testing\Empty Al Tube Testing on 24-6-17 at JNTUH\Pictures 24-6-17\IMG_9231.jpg |  | IMG_9239 |  |
| 40.2 | C:\Users\gpadmaja\Desktop\Technical\PhD-Final-8-11-19\PADMAJA Lab data\Al Tube Testing\Empty Al Tube Testing on 24-6-17 at JNTUH\Pictures 24-6-17\IMG_5177.JPG |  | IMG_4636 |  |

It can be noted that the enhancements from the superimposition of foam and tube strengths to the foam-filled strength vary proportional to the L/D ratio. However, the enhancements are greater for lower thickness values (about 50–55%) and lower for higher thickness values (about 15–18%), thus indicating material optimization with significant composite behaviour for very thin wall tubes, which are very prone to buckling locally. Additionally, the failure modes are illustrated in **Table 2** for unfilled and foam-filled aluminum tubes, through finite element analysis (FEA) validation.



**Fig. 1.** Cut section of failure mode in the specimen (40.2 D/t and 3.32 L/D)

Through failure modes, it can be observed that the infillment of high-density PU foam resists the local buckling, reducing the number of folds and its depth, and helping to improve the compressive resistance of the tube. This resistance is achieved due to the triaxial confinement and the rearrangement of the cell structure under loading, resembling a space frame, as shown through the cut section in **Fig. 1**.

Despite the enhancements in compressive resistance using sustainable infill high-density PU foam, there are no standard guidelines for designing high-density PU foam-filled aluminum circular tubes. Hence, the study continues to check the compatibility of previous CFST equivalent models that predict the compressive strength of this kind of structural element.

1. Analytical Models

The quasi-static axial compression results (refer to Table 1) for empty and high-density Pu foam-filled aluminum circular tubes from the above experimental investigations have been compared with analytical models from the present literature and international standards, utilizing the same material and geometric properties, as indicated by **Table 3** and **Table 4**, respectively.

**Table 3.** Material properties [6]

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Material | Density | Yield Strength | Ultimate Strength | Elasticity Modulus | Poisson’s ratio | Elongation |
|  | (kg/m3) | (MPa) | (MPa) | (MPa) |  | (%) |
| Aluminium | 2700 | 261.62 | 274.55 | 65404 | 0.33 | 7.6 |
| 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 4.** Geometric properties [6]

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Length (L mm) | Thickness (t mm) | | Diameter (D mm) | L/D | D/t |
| 200 | 2.0 | 60.3 | | 3.32 | 30.15 |
| 200 | 1.5 | 60.3 | | 3.32 | 40.20 |
| 300 | 2.0 | 60.3 | | 4.98 | 30.15 |
| 300 | 1.5 | 60.3 | | 4.98 | 40.20 |

* 1. Analytical Models of Empty Circular Aluminum Tubes

The analytical models proposed by the literature based on theoretical and experimental evaluations of hollow circular tubes with thin walls are presented in **Table 5**, along with a corresponding estimation of the mean compressive strength (computed for the experimental specimen. In the analytical models, the tube’s thickness and diameter are denoted by t and D, respectively. While M0 is the plastic bending moment, which can be computed using equation 1,

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stands for flow stress in Eq. 2, the average of yield stress ( and ultimate tensile strength (.

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Upon all the analytical models, the Abramovicz & Jones Model [8] aligns with experimental results. For specimens with D/t < 40, the analytical model overestimates with a variation of up to 9% and underestimates up to 7% for specimens with D/t > 40 However, all the models ignore the effect of L/D ratios and utilize the flexural capacity in between the elastic and plastic states, corresponding to the elastoplastic state.

**Table 5.** Mean Compressive Strength of Empty Circular Aluminum Tubes

|  |  |  |  |
| --- | --- | --- | --- |
| Semi-Analytical Models | Equation | Mean compressive strength (kN) | |
| D/t =40.20 | D/t 30.15 |
| Alexander [7] |  | 20.8 | 32.2 |
| Abramovicz & Jones [8] |  | **26.5** | **41.3** |
| Wierzbicki & Bhat [9] |  | 33.7 | 51.8 |
| Wierzbicki et al. [10] |  | 30.3 | 46.7 |
| Singace et al. [11] |  | 22.1 | 34.3 |
| Guillow et al. [12] |  | 35.6 | 57.6 |

Even though the specimens are categorized under short column theory, there will be minimal influence of length over them concerning global buckling. Therefore, the above models are suggested for modifications concerning global buckling and full plastic bending capacity.

* 1. Analytical Models of High-Density PU Foam-Filled Circular Aluminum Tubes

The analytical model for compressive strength is taken from British standard [13] developed for concrete-filled circular aluminum tubes considered as short columns as shown in Eq. 3.

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Where Aa, Ac, fck, fy,a and denotes circular tube cross-section area, infill concrete cross-section area, cylinder strength of concrete, yield stress of aluminum, and buckling factor, respectively.

The equation is well organized and designed to model the compressive capacity of a concrete-filled aluminum element by considering both the direct contributions of the aluminum envelope and the concrete infill, as well as their interaction during buckling. Factor 0.8 is a reduction coefficient that accounts for the non-ideal load transfer conditions between the concrete and the aluminum tube. And the term highlights the complex behavior of the composite system under compressive loads, where the aluminum’s buckling affects the load transfer to the concrete, As the aluminum tube buckles, it interacts with the concrete infill, potentially increasing the effective stress in the concrete due to the confinement provided by the aluminum tube, hence contributing to the overall compressive strength.

**Table 6.** Mean crushing strength of PU foam-filled circular aluminum tubes

|  |  |  |  |
| --- | --- | --- | --- |
| D/t | L/D | Mean Crushing Strength (kN) | |
| Experimental | Analytical [13] |
| 40.2 | 3.32 | 46.77 | 46.42 |
| 30.15 | 3.32 | 49.10 | 55.81 |
| 40.2 | 4.98 | 45.37 | 46.42 |
| 30.15 | 4.98 | 47.63 | 55.81 |

The experimental specimen’s compressive strength has been computed using the same physical properties and compared in **Table 6**. They are accurate for a D/t ratio of 40.2, but for a D/t ratio of 30.15, the values are overestimated. Although this model also ignores L/D effects, incorporating only local buckling effects utilizing the D/t ratio (refer Eq. 4). Therefore, it is recommended to incorporate the global buckling also for high-density PU foam-filled tubes as short columns.

1. Empirical Model using Machine Learning Algorithms

The above study on the compatibility of utilizing equivalent Composite Filled Tubes analytical models showcases the need to incorporate global buckling criteria for predicting compressive resistance, by highlighting the limitations of the analytical and semi-analytical models.

Although machine learning models are absent specifically for high-density PU foam-filled tubes, insights can be drawn from studies on composite systems to understand the efficiency of these algorithms. Xiao et al. [14] optimized the crashworthiness of polyurethane foam-filled origami thin-walled tubes, demonstrating that the CHC algorithm significantly improved specific energy absorption and reduced peak crushing force. Naser et al. [15] applied machine learning, specifically genetic algorithms and gene expression programming, to predict the structural response of concrete-filled steel tubular (CFST) columns, achieving superior accuracy over traditional design codes. Similarly, Kaveh et al. [16] found that deep learning models outperformed other regression techniques in predicting the buckling load of composite cylinders, despite both techniques showing effective predictions.

Building on these findings, the present study applies non-linear regression analysis with multiple independent variables, leveraging experimental data on compressive strength for PU foam-filled tubes to develop a reliable empirical model.

* 1. Framework for Machine Learning (ML) Modelling

In the view of objective of the study to develop empirical model for predicting the compressive strength of high-density PU foam-filled tubes aligning with existing equivalent models for composite tubes. The framework is proposed by integrating experimental investigations with ML algorithms, as shown in **Fig. 2**. The machine learning algorithms are purely based on the dataset, which is acquired through experimental tests, followed by data preprocessing. The governing parameters (independent variables) which influence the dependent variables are identified by the correlations, mechanics-based understanding of the composite system, and by reviewing existing theoretical models.



**Fig. 2.** Framework for ML modelling

The development of empirical models through artificial intelligence can be achieved by using either traditional machine learning algorithms, including regression analysis, random forest, etc., or deep learning algorithms such as Artificial Neural Networks (ANNs). The datasets are divided into training, validation, and testing data. Initially, the model is trained utilizing both dependent and independent variables, followed by the tuning of hyperparameters through validation. Further, the tuned model is tested with independent variables from the testing dataset, and the statistical indices are computed concerning both the actual and predicted values of dependent variables to evaluate the performance of the model. However, the selection of artificial intelligence algorithms is based on the quality of the dataset and the requirements of the empirical model.

For the present study, regression analysis is utilized through MATLAB (version R24b, 2024) software to develop the empirical equation for predicting the compressive resistance of the high-density PU foam-filled tubes. Despite the limitations of the data points, a pioneer study has been carried out to provide design guidelines for construction practices. The coefficient of determination (R2) is utilized as a statistical index (refer to Eq. 5) to evaluate the performance of the empirical models.

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

* 1. Correlation Analysis

Based on the raw data provided in Table 2 from the experimental investigations (refer to Section 2), a correlation analysis was conducted for both empty and high-density PU foam-filled aluminum circular tubes. The correlation matrix, as shown in **Fig. 3**, highlights the influence of local buckling (D/t) on compressive resistance, with local buckling having more control than global buckling (L/D). However, the L/D ratio also significantly impacts compressive resistance, suggesting that both D/t and L/D ratios should be considered in machine learning models to account for geometric instability through global and local buckling, respectively.



**Fig. 3.** Correlation matrix for (a) empty & (b) high-density PU foam-filled aluminum tubes.

Notably, the correlation analysis indicates that in foam-filled tubes, the influence of local buckling is reduced, allowing for a greater impact of global buckling. This observation aligns with experimental findings, where the foam infill stabilizes the local buckling effects in thin-walled tubes, leading to the development of progressive folds associated with global buckling.

* 1. High-density PU Foam Load-Displacement behaviour

The load (P) displacement (behaviour of high-density PU foam is curve fitted through linear and nonlinear regression analysis as shown in **Fig. 4**, with coefficient of determination of 0.65 and 0.76, respectively. The developed nonlinear empirical equation (Eq. 6) can be utilized to predict permissible load corresponding to allowable deflection, in a conservative manner.

(6)

Where, k is axial stiffness () and regression constants are 0.42, 0.22, -0.02, and 0.05, respectively.



**Fig. 4.** The Predicted versus actual data sets from regression analysis

The linear curve fitting does not incorporate energy absorption and densification region whereas the nonlinear curve fitting approach incorporates elastic and energy absorption regions followed by densification region with a deviation up to 10%.

* 1. Empirical Model for Empty Aluminum Circular Tubes

The Abramovicz & Jones Model [8] is modified by replacing flexural capacity at the elastoplastic region with plastic flexural capacity (refer Eq. 8) utilizing plastic section modulus (Zp) of hollow tubes (refer Eq. 9). Further, the global buckling criteria is incorporated in terms of longitudinal aspect ratio (L/D). The developed modified empirical model is shown in Equation 6.

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(8)

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Where regression constants are 0.0372, -0.0018, and -0.0027, respectively. The proposed model performance is evaluated by coefficient of determination as 0.98, demonstrating satisfied performance.

* 1. Empirical Model for PU Foam-Filled Aluminum Circular Tubes

Similarly, the British guidelines [15] for aluminum-filled tubes are modified based on the present experimental dataset by incorporating the global buckling criteria utilizing the L/D ratio. In general, the global buckling criteria is considered based on Euler’s elastic buckling load and slenderness ratio considering unsupported buckling length, but in the view of simple site calculations for design practices thus the global buckling criteria is considered in the gross manure. The developed regression model is shown in Eq. 10.

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Where are area and ultimate stress of infill high-density foam, and regression constants are -0.2114, 0.0033, and -0.0013, respectively. The performance is evaluated by the coefficient of determination as 0.99. Thus, the empirical model showcases allowable errors.

The empirical models proposed for both empty and foam-filled tubes are followed by short column theory assumptions, ignoring eccentricity effects and within the range of L/D from 3 to 5 and D/t of 30 to 45.

1. Comparative Analysis

The comparative analysis is carried out for the mean cursing strength of empty and high-density PU foam filled Circular Aluminum Tubes with varied D/t and L/D ratios and shown in **Fig. 5** and **Fig. 6** respectively, considering experimental results, relevant analytical model and empirical model developed in the present study.

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

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

The comparative analysis demonstrates that the empirical model produces accurate results when accounting for length variation, effectively incorporating global buckling criteria. However, the predicted values are up to 2% lower than the experimental values, which can be attributed to the model’s conservative approach.

1. Conclusions

The study’s conclusions can be ascertained as follows:

1. The study found that compressive resistance decreases with thinner metal envelopes, which are more prone to local buckling. This issue can be mitigated by infilling with high-density (150 kg/m³) PU foam, which effectively resists local buckling. The foam reduces the number and depth of folds all over the length and resulting in progressive folds, thereby enhancing the overall compressive resistance.
2. The improvement in strength due to high-density PU foam infill varies according to the L/D ratio. Notably, thinner tubes exhibit a substantial increase in strength (50–55%) compared to thicker tubes (15–18%), highlighting significant material optimization, particularly in thin-walled tubes that are susceptible to local buckling.
3. The Abramowicz & Jones [8] model was found to closely match the experimental results for empty circular aluminum tubes. However, it tends to overestimate or underestimate compressive strength depending on the D/t ratio. The study suggests modifications to better account for global buckling and the full plastic bending capacity.
4. The British Standard [13] equation effectively models the compressive strength of concrete-filled aluminum tubes, considering the interactions between aluminum and concrete under buckling conditions. However, it does not account for the effects of global buckling.
5. The empirical models developed for both empty and foam-filled tubes demonstrate accuracy across different lengths, incorporating global buckling criteria.
6. The correlation analysis comparing empty tubes to foam-filled tubes revealed a reduced influence of the local buckling parameter (D/t) on compressive resistance, this finding is consistent with the experimental investigations.

High-density PU foam as an infill material exhibits significant composite behavior, enhancing tube strength through material optimization and providing substantial resistance to local buckling, with minimal influence from global buckling on compressive resistance. While existing CFT analytical models for both empty and foam-filled tubes are generally effective, they overlook length variation and global buckling factors. Despite the limited dataset, this study pioneers the design practices for high-density PU foam-filled circular aluminum tubes, recommending an empirical model for predicting compressive strength with practical applications in construction. Future research could be enhancing the preliminary models proposed through greater datasets developed through numerical investigations under various conditions.

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