UNIVERSITI TEKNOLOGI MARA

AN EMPIRICALLY DERIVED EMBEDMENT YIELD LOAD EQUATION FOR THE DESIGN OF BOLTED CONNECTIONS USING *GIGANTOCHLOA SCORTECHINII* AND *DENDROCALAMUS ASPER* FROM MALAYSIA

SITI SUHAILA BINTI SUDERMAN

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ABSTRACT

Bamboo is recognised as one of the most promising sustainable construction materials due to its rapid growth, renewability, and ability to reduce carbon dioxide (CO_2) emissions, thereby contributing to climate change mitigation. Despite these advantages, its application as a structural material remains limited because of the lack of reliable connection design data, particularly for bolted bamboo connections. This study aims to develop empirically derived connection design properties for two Malaysian bamboo species, namely *Gigantochloa scortechinii* (*G. scortechinii*) and *Dendrocalamus asper* (*D. asper*), to improve the reliability of structural bamboo connection design. To achieve the first objective, embedment yield load equations were derived using 1,440 embedment strength specimens tested with three bolt diameters (6mm, 10mm, and 12mm) at the top, middle, and bottom culm positions. Four embedment test configurations were investigated, namely Single Half-Hole (SHH), Double Half-Hole (DHH), and Full-Hole according to ASTM D5764-97a (FHA), together with the Full-Hole method according to EN 383:2007 (FHE. The physical properties of bamboo, including diameter of culms (D), bamboo wall thickness (t), moisture content (w) and density (ρ) were determined, while the mechanical properties, including yield load (F_{yield}), embedment strength (f_h) and characteristic design values, were statistically analysed using correlation analysis and regression modelling in SPSS to establish empirical prediction equations. To fulfil the second objective, the embedment strength results obtained from ASTM D5764-97a and EN 383:2007 were compared to evaluate the influence of different testing methodologies on the derived design properties. The comparison demonstrated that both standards produced consistent trends in embedment behaviour, although differences were observed due to their respective specimen configurations and yield determination procedures. The third objective evaluated the applicability of the European Yield Model (EYM) through an energy-based analytical approach to predict the shear capacity of bamboo culm connections. The derived embedment equations and experimentally determined bolt yield moments were incorporated into the EYM framework to establish the characteristic yield capacity and identify the governing failure modes for the bamboo connections. Finally, to satisfy the fourth objective, 36 sets samples of Single-Shear Connection (SSC) tests were conducted for both bamboo species to validate the predicted shear capacities obtained from the energy-based model. A strong correlation was obtained between the predicted and experimental shear loads, confirming the applicability of the developed empirical equations and the energy-based EYM approach for Malaysian bamboo. The results showed that both *G.scortechinii* and *D. asper* possess densities ranging from approximately 700 to 900kg/m³, embedment strengths between 30 and 50 N/mm², embedment yield loads of approximately 3000 to 5000N, and experimental SSC shear capacities ranging from approximately 1000 to 3000N. These findings demonstrate that both bamboo species possess sufficient mechanical performance for structural connection applications and provide reliable design data for future bamboo engineering. The developed empirical equations contribute to the standardisation of bamboo connection design and provide a foundation for the wider implementation of bamboo as a sustainable construction material. Future studies should investigate the long-term durability and environmental performance of bamboo connections under varying service conditions.

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CHAPTER 1
INTRODUCTION

1.1 Research Background

Generally, bamboo is a tall tropical plant with hard, woody, and hollow stems. In 2004, Azmy et al. reported that bamboo naturally grows widely and takes 3 to 5 years before it can be used as a structural material (Zhang et al., 2013; Li et al., 2011; Chen et al., 2020; Lu et al., 2020; Lou et al., 2021). Approximately 140,000 square metres of bamboo forests are found worldwide, demonstrating that the plant is highly abundant (Tang et al, 2019). Asia, especially Southeast Asia, extensively grows bamboo because it thrives in the ideal temperature and humidity conditions found at lower latitudes. It is considered to be the second most important forestry resource in the region (Zhou et al., 2018). People love bamboo because it grows back quickly and breaks down naturally, making it a great eco-friendly substitute for steel and concrete, which are common building materials (Madhushan et al., 2023).

Meanwhile, bamboo forests cover approximately 5% of the total forest reserve in Malaysia (Abd Latif,1987). Baharuddin. N (2020) from the Timber Industry Board under the Ministry of Plantation Industries and Commodities of Malaysia highlighted that there are 45%, 31% and 24% of bamboo plantations in Sarawak, Peninsular Malaysia, and Sabah, respectively, with 59 species, including 39 of the local species. Bamboo also has been listed as a sustainable building material because it is renewable and, when used as a culm, consumes less energy, and causes less pollution (Chen et al., 2020; Bouville et al., 2014; Song et al., 2018., Nitesh et al., 2018; Xia et al., 2016). In contrast to bamboo, the currently established material (i.e., concrete, fibre polymer, steel) faces challenges such as high energy consumption, pollution, and non-renewability, all of which have been identified as drawbacks for future sustainable construction materials.

Bamboo is a renewable, widely available natural resource that can grow in almost any climate (Janssen. 2000; Liese and Kohl, 2015; Ghavami 2005; Sharma et al, 2015). The physical and mechanical properties of bamboo significantly impact its strength as a building material (Masdar et al., 2014). Several factors influence the mechanical properties of bamboo, including density, botanical species of bamboo, age