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Seismic reliability analysis of a timber steel hybrid system

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ABSTRACT

Seismic reliability analyses account for the inherent uncertainties in both the actions (earthquakes) and the reactions (properties of the structural systems) of a structure. To predict the failure probability of a structure, the system response due to external loads is usually estimated by a numerical method. In this paper, seismic reliability analyses were performed on a novel timber-steel hybrid system labelled FFTT (Finding the Forest Through the Trees) system. The FFTT system utilizes mass-timber panels to resist gravity and lateral loads and interconnecting steel members to provide the necessary ductility for seismic demands. To reduce the computational effort for reliability analyses, Genetic Algorithms (GA) and Analysis of Variance in combination with response surface methods were applied and compared. Uncertainties involving ground motions, seismic weight, connection properties of the lateral load resisting system, and ductility factor were considered in formulating the performance functions. Mean and standard deviation of peak inter-storey drift were selected as performance criteria. Nonlinear dynamic analyses were run to generate the response database for the FFTT system and the reliability index was calculated using second-order reliability methods. The results showed that the GA method was superior and that the ground motion was the most significant factor for structural reliability, while the ductility factor, the structural weight, the hold-down and connection stiffness also played significant roles.

1. Introduction

1.1. Novel timber-steel hybrid systems

With construction professionals and designers seeking lower carbon footprint building alternatives and more sustainable materials, there is a growing interest to expand the tall wood building sector worldwide. Pure wood construction, however, creates challenges, such as a lack of ductility in seismic design, lack of weight against overturning forces, and possibly lack of stiffness in wind design. To overcome these challenges, a variety of wood-based hybrid solutions have been proposed such as hybrid timber-steel structures. Steel elements provide ductility, high tensile capacity, and stiffness, while timber is used for providing enclosure, reducing the environmental impact (by reducing greenhouse gas emissions and storing carbon in the building), weight reduction (resulting in reduced transportation costs and reduced design base shear forces) and high strength parallel to grain [1].

The Scotia Place [2] in New Zealand is an example of a 12-storey timber-steel hybrid structure. The building consists of a concrete basement and transfer slab at the ground level; the structural steel superstructure is combined with timber diaphragms. The Kanazawa M Building, constructed in 2005 in Kanazawa, Japan, is a 5-storey building with four timber-steel composite levels supported by a reinforced concrete first floor. The building system consists of steel-timber composite frames, concrete floors, slabs and roof, and plywood walls [3]. The Pyramidekogel tower in Austria, is a 100 m high observation tower that extends over ten levels with two platforms. The curved glulam columns that provide vertical and lateral support are supported in their weak direction by Hollow Structural steel Sections (HSS) forming elliptical rings and diagonal struts [4].

Two other noteworthy built examples are the “H8” in Bad Aibling, Germany, constructed in 2011 [5] and the “Brock Commons” in Vancouver, Canada constructed in 2016 [6]. H8 is an 8-storey building comprised of CLT floors and CLT walls with a concrete core. The panelized system permitted a construction time of 16 working days, or one storey every two days. Brock Commons is currently the tallest contemporary hybrid wood building with an 18-storey (53 m) wood structure and was completed four months ahead of schedule. A concrete core is used to resist lateral loads while heavy timber beams are used to carry the gravity loads. Both buildings use the encapsulation approach with gypsum wall panels to achieve the required fire resistance ratings.

A conceptual design of a timber-steel hybrid system “Finding the Forest Through the Trees (FFTT)” was introduced to the public in the Tall Wood Report [7]. It is a structural system that aims to challenge

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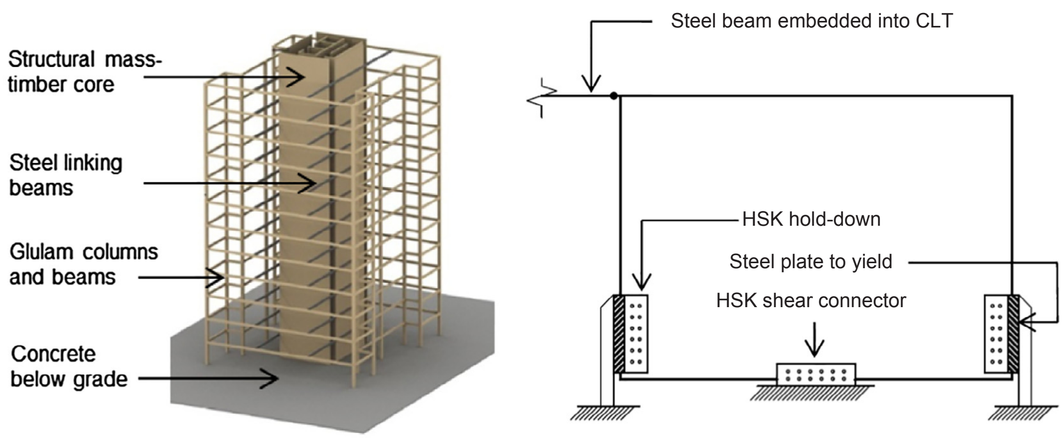

Fig. 1. Schematic of (a) FFTT system for option 1 [7] and (b) HSK hold-down for FFTT system [12].

concrete and steel construction for tall buildings. The FFTT system consists of balloon-framed mass-timber panels and is designed using a "strong column–weak beam" approach. Large format mass-timber panels such as cross-laminated timber (CLT) are used as vertical load carrying elements, lateral shear walls, and floor slabs. The "weak beam" components are made of steel sections bolted to the mass-timber panels to provide ductility. Concrete is only used for the foundations up to the grade level. Four different design options varying in number and location of the mass-timber shear walls are proposed for building heights varying from 12 to 30 storeys. Option 1 is designed for buildings up to 12 storeys and relies on glulam columns to resist gravity loads, and CLT core walls with linked steel beams to provide lateral resistance, see Fig. 1a.

The steel beams are designed to yield and absorb seismic energy. Previous experimental and analytical research [8–10] demonstrates that the type of steel profile has a significant impact on the performance of the CLT wall to steel beam connection. Wide flange W sections achieve higher moment capacity than HSS sections. The HSS sections, however, provide higher ductility and are not prone to out-of-plane buckling. Fairhurst et al. [11] and Zhang et al. [12] demonstrated that a calibrated concentrated rotational spring using the OpenSees Pinching4 material model [13] used for the beam-wall interface can efficiently capture the complete nonlinear behavior of the connection including cyclic strength and stiffness degradation caused by steel yielding and timber crushing.

To provide resistance against the overturning moments caused by lateral loads such as wind or seismic action, hold-downs are installed to transfer the vertical uplift forces to the foundation. For the FFTT system, the Holz-Stahl-Komposit-System (HSK-System)™ [14], as shown in Fig. 1b, is proposed as the hold-down solution. The HSK system consists of steel plates with a prescribed geometry glued into slots of the mass-timber panel using an approved two component adhesive. The capacity of an HSK connection is governed by the minimum of: (i) the steel plate, (ii) the adhesive bond, and (iii) the wood capacity. The connection can be designed for ductile steel failure under quasi-static as well as reversed cyclic loading. Previous research demonstrated that the HSK system exhibits stiff performance, high ultimate load capacity, ductile behavior and predictable fatigue performance [15,16]. The HSK connection has been successfully applied, e.g. in the "flying staircase" of the Earth Science Building in Vancouver [17].

1.2. Reliability methods

Reliability methods have been established to take into account the uncertainties involved in the analysis of an engineering problem. Generally, failure, an undesired or unsafe state of the structure, is defined in terms of a limit-state function $g(X)$ by the set $F = \{X: g(X) < 0\}$, $Z = g(X)$ which separates the failure domain from the safe domain [18]. The primary objective of reliability analyses is to quantify risks by computing the failure probability, P_f. The reliability problem, i.e. computing P_f, has two ingredients: (i) random variables that describe the uncertainty, and (ii) a limit-state function that defines failure. The limit-state function $g(X)$ can be expressed as the difference between the resistance $R(X)$ and the demand on the system $S(X)$. The failure probability, P_f, is determined as:

$$P_f = P[g(X) \leqslant 0] = \int_{g(X)\leqslant 0} f_X(X) d_{x_1} d_{x_2} \cdots d_{x_n} = \Phi(-\beta) \tag{1}$$

where β is the reliability index of the system.Solving Eq. (1) analytically is often not possible; therefore, approximate methods have been developed such as first-order reliability method (FORM), second-order reliability method (SORM), and importance sampling (IS) [18]. In cases where the linearization of the highly nonlinear limit-state function may lead to inaccuracies, SORM is more appropriate to approximate the limit-state function.

The Response Surface Method (RSM) is a statistical method which uses a sequence of designed experiments (or parameter combinations) to obtain a system response [19]. Based on this procedure, the relationships between several explanatory variables and one or more response variables can be explored. However, it is difficult to find a simple and appropriate equation to represent a RSM database which uses a sequence of designed parameters to obtain structural response from a mass of structural modeling. One possibility is to consider a constant mass and stiffness aside from the ground motion and error uncertainty [20]. With an increased number of random variables, more items and higher orders will appear which increases the difficulties when preparing the reliability analysis performance function. Therefore, the present paper utilizes two different methods: Analysis of Variance (ANOVA) and Genetic Algorithm (GA) in order to predict and compare a simplified response surface equation reliability analysis.

1.3. Stepwise Analysis of Variance (ANOVA)

Analysis of Variance (ANOVA) consists of calculations that provide information about levels of variability within a regression model and form a basis for tests of significance [21]. Before applying ANOVA in response surface procedures, a regression to fit the obtained response surface data is performed. Usually, a multivariate polynomial function is used as a potential regression model. All possible combinations of the random variables are used to develop the regression equation and the coefficients of the equation can be obtained by minimizing the square errors between the actual response data and the fitted response surface. However, as the order of random variables increases, so do the number of components that need to be considered in the polynomial function which results in a more complex reliability analysis. In this case,