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Computational benefits of fast non-linear analysis for performance-based wind design of tall mass-timber buildings

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SUMMARY

Performance-based wind design is increasingly gaining attention because it enables efficient design of structures for targeted performance objectives. However, it requires iterative assessment of global and component responses under multiple wind hazard levels. Such procedures can be computationally demanding for systems exhibiting nonlinear behaviour at design-level and extreme winds. Prior studies have introduced a strain-driven dynamic shakedown method, but the method provides only shakedown-level results, lacks full time-history responses, and is unsuitable for mass timber systems that typically exhibit pinching and degradation early in their nonlinear response. Recent studies have proposed adaptive fast nonlinear analysis (FNA) techniques to address these limitations, yet applications have been limited to steel structures. Recognizing the modelling complexities of mass timber lateral systems, this paper develops an adaptation of the FNA framework for performance-based design of tall mass timber buildings with braced timber frames. Validation against direct-integration analysis demonstrates the method's accuracy and efficiency.

Keywords: *Mass-timber, Braced timber frames, Performance based wind design, fast nonlinear analysis.*

1. INTRODUCTION

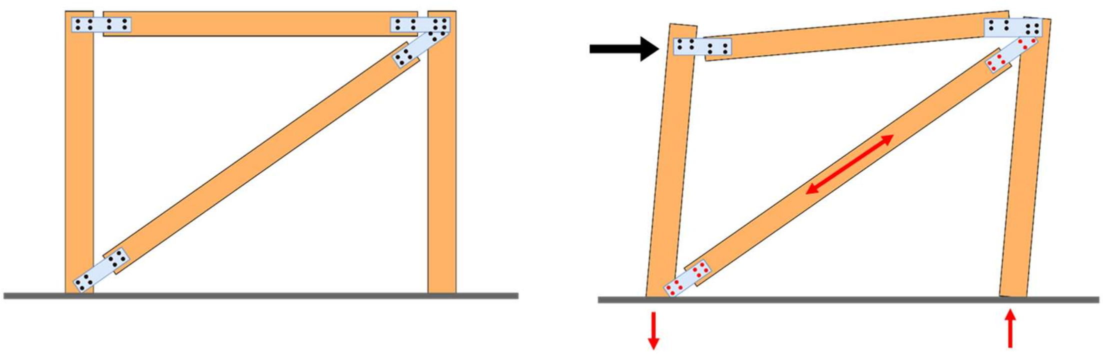
Timber is a renewable, low-carbon material with relatively low embodied energy, making it an attractive option for meeting growing urban housing demands while contributing to environmental sustainability (Karacabeyli and Lum 2022). For tall mass-timber buildings, wind loads often govern structural design because timber structural members are lighter and less stiff than comparable steel or concrete structures (Bezabeh et al. 2018a, 2020). To fully leverage mass-timber main wind force resisting systems (MWFRSs), such as braced timber frames (BTFs), the use of advanced performance-based wind design (PBWD) methodologies is essential.

Performance-based wind design is increasingly recognized as a powerful framework for achieving targeted structural performance through an efficient design. A central aim of PBWD is to assess structural inelastic behaviour and reliability under wind events. PBWD implementation requires repeated evaluation of global and component responses across multiple wind hazard levels. This becomes particularly demanding for systems that undergo nonlinear behaviour at design-level and extreme wind demands. While strain-driven dynamic shakedown methods have been proposed (Chuang and Spence 2022) to identify critical failure mechanisms such as ratcheting and low-cycle fatigue, they are limited to shakedown-level solutions and are incapable of generating full time-history responses. Moreover, these methods are not applicable to mass timber systems, which typically exhibit pinching and degradation early in their nonlinear range.

To address these challenges, recent studies have explored adaptive fast nonlinear analysis (FNA) techniques that adjust step size, modal participation, and the set of potentially nonlinear elements to reduce computational cost (Li et al. 2023). However, these developments have been applied only to steel structures. Noting the modelling complexities unique to mass-timber lateral systems, this study extends the FNA framework to predict the nonlinear wind response of tall mass-timber buildings. The proposed framework is evaluated through comparisons of time-history and hysteretic responses with classical direct-integration analyses, demonstrating both accuracy and computational efficiency.

2. BRACED TIMBER FRAME

BTFs (Figure 1(a)) provide an efficient lateral system by aligning timber members with their grain orientation to resist tension and compression. BTF end connections have also been studied under seismic loads through analytical and experimental investigation and demonstrated strong performance (Chen et al. 2019). The lateral force-resisting mechanism of BTFs is analogous to that of a conventional truss, where resistance is primarily developed through axial actions. Under lateral loading, the diagonal brace engages in either tension or compression depending on the direction of loading, while the edge columns provide complementary axial resistance to complete the load path as illustrated in Figure 1(b). The 2020 National Building Code of Canada (NBC 2020) includes seismic force modification factors for limited and moderately ductile braced timber frames. Aside from prior studies focused on their seismic performance, the behaviour of BTFs under wind loading remains largely unexplored.



(a) (b)

Figure 1: (a) Braced timber frame (b) lateral response of braced timber frames

NUMERICAL MODELING OF BRACED TIMBER FRAMES

A three-dimensional numerical model of BTFs that incorporates *elasticTimoshenkobeam* elements that represent the beam, column, and portion of the bracing except for the rivet connections was developed in *OpenSeesPy*. This finite element model is developed for validation of the proposed FNA framework through direct integration based non-linear analysis. The columns are modelled as a continuous element while the beams are connected to the columns with pin ends to avoid moment resistance. The rivet connections at the two ends of the brace are represented by *Pinching4* element with parameters calibrated based on the experiment conducted by FPInnovations, as shown in Fig 2.

ADAPTATION OF FAST NONLINEAR ANALYSIS FOR BTFs

Rapid time history analysis of nonlinear systems with a specific number of predefined nonlinear elements can be carried out using fast nonlinear analysis. The computational speed of the FNA method is several magnitudes faster than that of the traditional NLRHA. Nonlinear response in BTFs is limited to the brace end connections making FNA a suitable approach. For validation of the FNA results, traditional NLRHA was initially conducted using the above discussed *OpenSeesPy* model for a prototype 16-story building hypothetically located in Toronto, Canada.

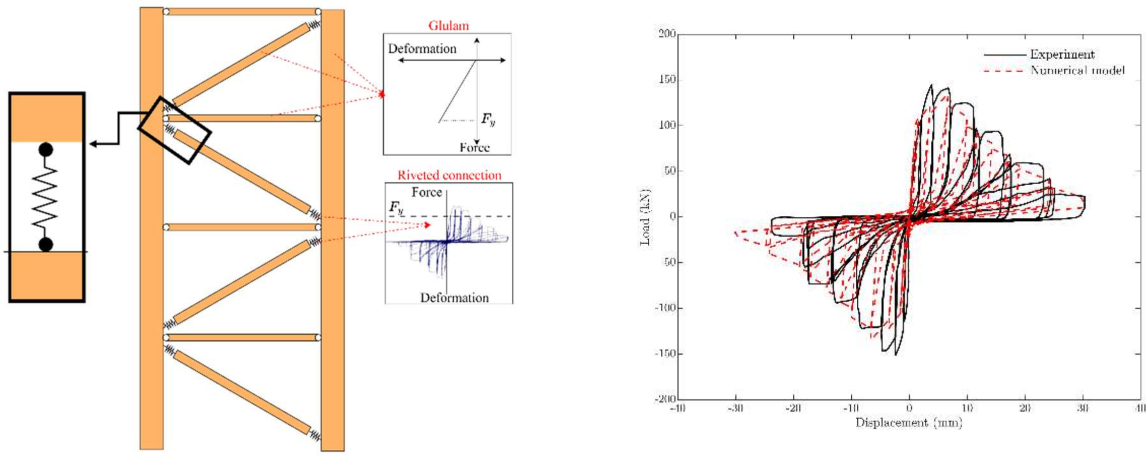


Figure 2: Nonlinear modelling and analysis of BTFs: (a) numerical modelling approach, (b) component-level validation of the model

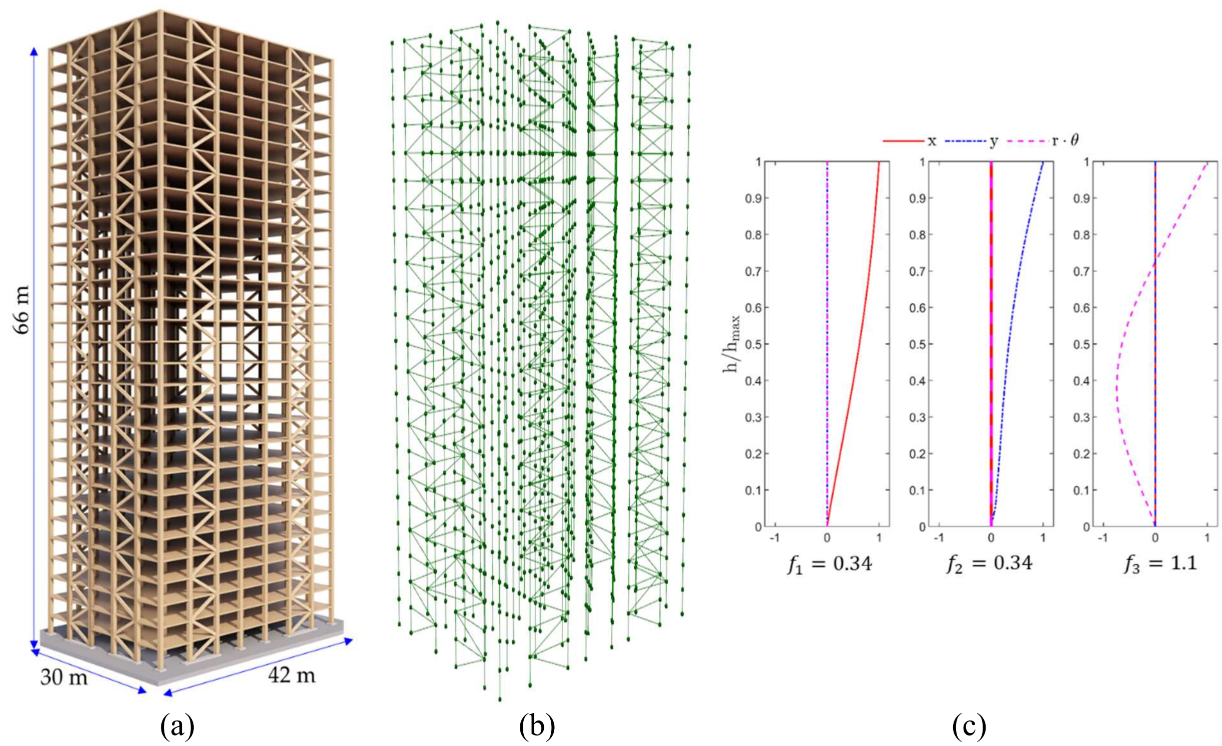


Figure 3: 16-story prototype building design (a) 3D-rendering (b) 3D-numerical model (c) mode shape and frequency

RESULTS

For the prototype 16-story BTF building, global and component responses in terms of story drifts and force-deformation hysteresis were recorded. The responses were compared with corresponding performance limits under each wind load realization to define failure according to the latest ASCE PBWD Prestandard. Figure 4 shows the component level response of selected brace-end riveted connection response under 700-year MRI wind loads. The results indicate the proposed FNA-based analysis properly captures both the global and component level time history and hysteretic responses with computational efficiency.

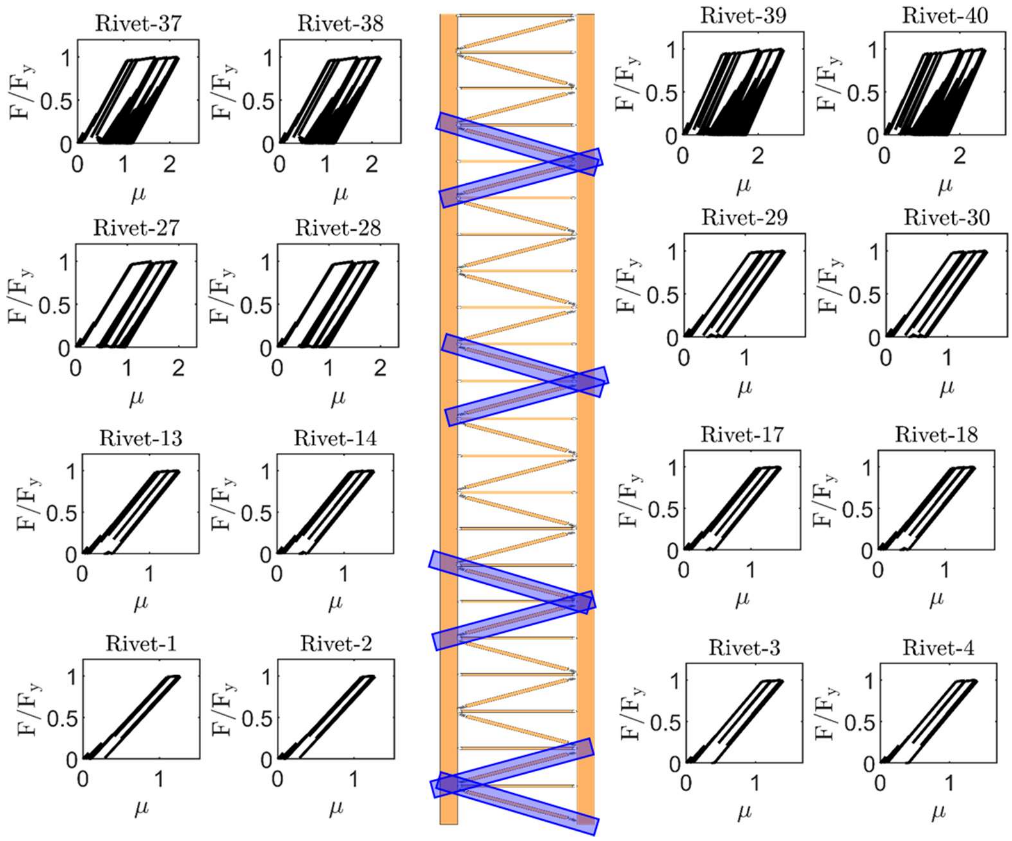


Figure 4: Response of riveted brace end connections under 700-year MRI wind load.

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