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Finite element analysis of low-rise non-engineered residential buildings in Dominica under hurricane loads

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SUMMARY
Without the measured understanding and quantification of a region's building stock vulnerability to wind, the development of feasible damage mitigation solutions is limited, as is their evaluation in improving the building performance. In an attempt to address the relative lack of engineering-based wind vulnerability methodologies developed for the Caribbean, this study identified the most common Dominican residential building typologies and analysed their structural response to hurricane loading. A detailed field survey was developed to undertake structural inspections of over 40 of Dominica's low-rise, non-engineered residential buildings. The structural data are examined to build representative prototype models of four common residential building typologies of varying wind fragility. These typologies are: timber buildings with lightweight hip roofs; timber and concrete masonry buildings with light hip/hip & valley roofs; concrete masonry buildings with light hip/hip & valley roofs; and concrete masonry buildings with heavy flat roofs. An iterative process is developed to build the prototype models to analyse their structural response to wind loading applied in a quasi-static manner and calculated according to equations in ASCE-22. The numerical analysis is undertaken using commercial software SAP2000. The methodology used in this study is outlined, and the findings, as well as the limitations, are discussed.

Keywords: FEM, Caribbean, Hurricanes

1. INTRODUCTION

Hurricanes may remain the most dominant and destructive natural peril negatively impacting the economies of Caribbean states. Non-engineered private-sector homes are considered subject to the largest risk, with most of their structural data difficult to access for vulnerability assessment.

He et al. (2017) note the utility of fragility/vulnerability curves accounting for the critical structural responses quantifying building performance. This requires a complete, validated finite element building model, preferably stochastic, rather than deterministic. Non-engineered wooden buildings are expected to be one of the most fragile typologies to wind; however, previous studies which have built full numerical wind analysis models of low-rise timber buildings have been found to exclude elevated buildings and have not necessarily produced fragility/vulnerability curves.

This paper presents a finite element methodology being developed for the analytical wind vulnerability assessment of elevated timber buildings with lightweight hip roofs. The remaining three low-rise, non-engineered housing typologies investigated will be addressed in future works.

2. METHOD

To assess the wind vulnerability of timber frame buildings, the proposed finite element methodology has been developed in two stages: 1) an initial test of the robustness of the timber frame and 2) a full assessment of the building, including cladding. This paper details the first stage of the methodology, with the second to be similarly detailed in future works.

2.1. Damage Analysis

An island-wide building damage assessment was led by the United Nations Development Program (UNDP) in Dominica within several months following Hurricane Maria (2017). The UNDP data was examined to estimate the population of single-storey timber buildings with galvanised sheeting hip roofs and locate and survey a representative sample. A total of 262 houses were identified (on pillars or shallow foundations), which fell into the timber typology of interest, and were most likely to have been solely impacted by wind hazard during the hurricane. A larger percentage of these homes suffered extensive roof damage rather than extensive wall damage. As such, the results presented in Section 3 focus on the roof structure of an index building model.

2.2. Field Survey

To address the relative data scarcity on Caribbean residential construction, a detailed field survey was undertaken in Dominica by University College London (UCL). Structural inspections were carried out for three timber frame buildings across the island, and their structural details were used to build a representative single-storey index building. The building is elevated on reinforced concrete pillars, with anchor bolts connecting the timber frame to the foundations.

2.3. Structural Model

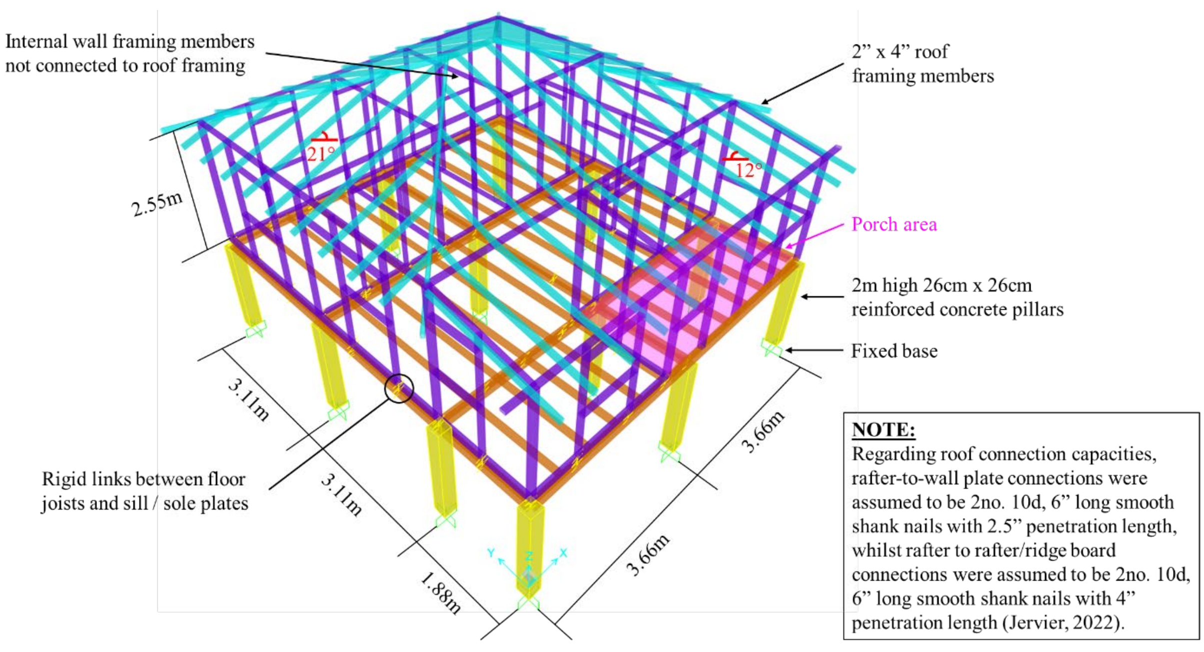

Figure 1. 3D frame model of elevated timber building with hip roof in SAP2000

Initially, a 3D frame model is built for the structure using the commercial finite element (FE) software SAP2000 (CSI, 2016), as shown in Figure 1. All frame-to-frame joints are initially modelled as continuous before sampling their response under wind loading and substituting their connections with non-linear link elements with properties representing axial, shear and rotational degrees of freedom and stiffness of nailed joints assumed from literature where possible. Applied loads are residential live loads and wind loads according to ASCE 7-22 (ASCE, 2022). The self-weight of the structure is also included in the analysis.

2.4. Failure Analysis

During Hurricane Maria (2017), the maximum 3-s gust wind speed over land was recorded as 165mph or 74m/s (Gibbs, 2017). In the FE model, distributed wind forces are applied to the frame elements in an incrementally increasing manner from zero to 74m/s, expecting to cause systemic failure. The model is initially assumed to have zero damage. Two basic failure modes for the roof members are explored; pull-out and pullover failure of the nails, for which the nail capacities are calculated following the equations used by Song et al. (2020). Wind loads are calculated and applied to the frame according to ASCE 7-22 Case 1, with wind approaching perpendicular to the front elevation. This is done to analyse the windward roof-to-wall junction with a large overhang over the porch. Worst-case single values are taken for external and internal pressure coefficients.

3. RESULTS

With moment transferring connections maintained at nodes and without load redistribution considered initially, Figure 2 shows that at the maximum wind speed, pull-out at rafter to ridge board/rafter/wall plate connections may be considered the more critical mode of failure for the roof framing of this structure compared to pullover failure. Pull-out failure of the rafters may be speculated to initiate at the bottom right-hand corner of Figure 2a, over the porch, where the highlighted hip rafter is shown to be susceptible to both modes of failure.

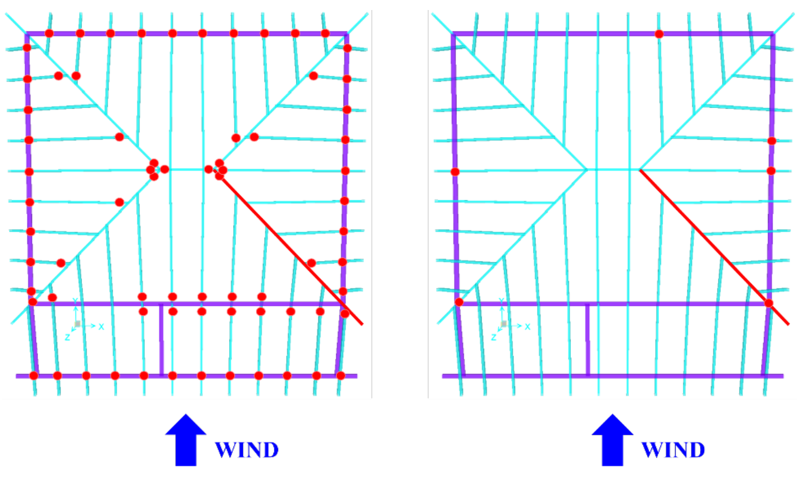

Figure 2. Plan view of roof structure and perimeter wall plates in SAP2000. a) Rafter-to-rafter / ridge board and rafter-to-wall plate connections highlighted where nail pull-out capacity is exceeded. b) Nail pullover capacity exceedance highlighted. Analysis considers wind loading at a max. 3-s gust wind speed of up to 75m/s at 10m height

Figure 3 shows that the pull-out capacity ($P_{n.out}$) at the rafter to ridge board connection for 2no. nails is likely to be exceeded at lower wind speeds relative to the pullover capacity ($P_{n,over}$) at the rafter-to-wall plate connection for the hip rafter highlighted in Figure 2. It should be noted that for both failure modes, capacity is exceeded well before the maximum wind speed is reached.

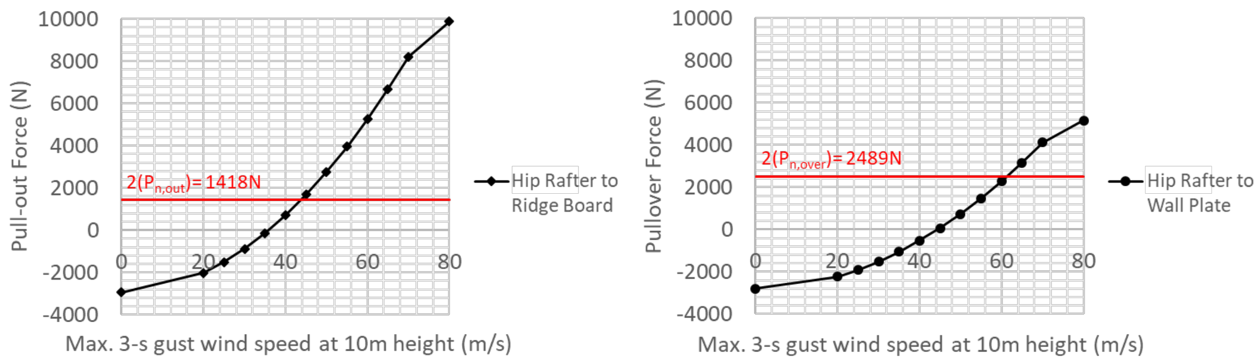

Figure 3. a) Pull-out force at rafter to ridge board connection, and b) Pullover force at rafter to wall plate connection for bottom right hip rafter against max. 3-s gust wind speed at 10m height

5. CONCLUSIONS

A complete, validated finite element building model, stochastic rather than deterministic, would lend itself indispensably toward the development of vulnerability curves which capture building performance against hazards. When faced with non-engineered structures and hence a relative lack of structural data, this paper demonstrates the benefit of developing the assessment process in two parts. For timber structures, the robustness of the frame is first tested, with the stiffness of critical connections identified and adjusted accordingly, before modelling the cladding against hurricane loads. For common low-rise, non-engineered timber residential buildings in Dominica, numerical analysis has shown that roof member connections and roof-to-wall connections are vulnerable to wind damage during hurricanes. It is expected that consideration of other aspects of timber buildings, and eventually, the extension to different typologies, will mirror findings for wind hazard and that, by in large, current construction practices require urgent attention.

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