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Effect of human error on the reliability of roof panel under uplift wind pressure

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ABSTRACT

Post disaster investigations indicate that the roof damage often occur during strong wind events. Human or construction error could be one of the contributing factors for the observed damage. In this study, a survey was carried out at the IRLBH (The Insurance Research Lab for Better Homes) facility (at the University of Western Ontario) to inspect the quality of construction, especially the fasteners used to fasten the plywood roof panels to the roof trusses. Statistics of missing nails which are required for the fastening are obtained. It was suggested that the occurrence of the missing nail could be modeled using binomial process with the occurrence rate of 1.5%. The effect of the missing nail on the statistics of the panel uplift capacity to wind pressure, which are evaluated using the nonlinear finite element techniques by considering the uncertainty in nail withdrawal behavior, is assessed and compared to those without missing nails. Also, the influence of the missing nail on the reliability of roof panel under wind load is investigated. The implication of the results on the codified design is discussed.

1. Introduction

The damage to and insured loss of light frame wood houses caused by windstorms are rising. This trend is partly due to increased population and construction in the coastal areas. Failure of a single roof panel has the potential to drastically increase insured loss due to water penetration during windstorms [1]. This problem is compounded by the fact that wind-induced failure is frequent and often initiates at roof sheathing panels. Failure was also observed for newer homes built to more recent and stringent building codes [2].

Numerical analyses and experimental tests have been conducted to investigate the uplift capacity of typical roof sheathing panels, considering that the wind pressure can be treated as a time-invariant or static uniform pressure [3–7]. None of the mentioned studies were carried out by considering spatio-temporally varying wind pressure and nonlinear dynamic analysis. A valuable parametric investigation of the impact of construction quality on the performance of light-frame wood construction was reported by van de Lindt and Dao [7]. Although, no detailed actual survey or statistics on missing fasteners for the construction was presented or used, and the wind load was modeled as a uniform static wind pressure rather than more realistic spatio-temporally varying wind pressure, an actual roof that failed during hurricane Katrina was considered for their analysis. The Insurance Research Lab for Better Homes (IRLBH) at the University of Western Ontario, a state-of-the-art test facility, is equipped with pressure loading actuators, which allows the investigation of the performance of houses as well as construction quality under environmental actions, including full-scale wood frame houses under wind loading.

An inspection of the results from damage surveys [8] and details of newly constructed houses indicates that, similar to any other construction or manufacturing process, error does occur – some of the nails used to fasten the roof panels to the roof trusses may be missing or improperly installed. The missing or improperly fastened nails are likely to affect the panel uplift capacity and its reliability under wind load.

The influence of construction quality on the reliability of structures is a well-known problem. Ellingwood [9] indicated that it is not surprising that structural failures rarely occur because of high loads and low strengths, since design codes are developed to cope with the uncertainty in loads and structural resistance. The proportion of failures attributed to human error varies from about 75%–90% [10–13]. However, error in construction is difficult to quantify. This is partially due to limited accessibility to construction sites to carry out detailed inspection, as well as the fact that failures attributed to poor construction quality or human error are not considered explicitly in calibrating design codes. The

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subject of human error and structural practice was also discussed by Allen [14] in terms of how mistakes are made and discovered. As the building process involves a wide variety of tasks carried out by humans, research focused on human error needs a multidisciplinary approach with expertise from psychology, forensic engineering, sociology and quality management [15]. This range of consideration is valuable, but is beyond the scope of this study. Rather, we take the advantage of having complete access to the two-story full-scale wood frame test house during its construction at the IRLBH facility for the purpose of quality inspection. More specifically, we inspected and surveyed the fastening of the roof panel, nail-by-nail, for the full-scale two-story test house, which was constructed at the IRLBH facility [16–18] by students from Fanshawe College in London, Ontario, Canada. Although the quality of the construction, according to more than 20 local building inspectors, was representative of average construction quality, this assertion may not be shared by other practicing engineers because of the laboratory setting and only a single house specimen. However, the results, at least, could be considered as a lower bound on the human error or used as a baseline case.

The collected information on the quality of fastening was employed in this study to assess the frequency of missing or improperly installed nails used to fasten the plywood roof panels. This frequency is incorporated to assess the roof panel uplift capacity. For the assessment of the statistics of the panel uplift capacity, a spatio-temporally varying wind pressure, rather than a uniform static wind pressure often used in the literature was considered. A finite element model is used to represent the panel and fasteners and a nonlinear dynamic analysis with ramp load is employed. The use of this approach is justified because it provides sufficient accurate estimates of the panel uplift capacity as compared to those obtained based on the nonlinear incremental dynamic analysis results [19]. Parametric investigation of the uplift capacity of the panel is carried out by considering nonlinear force–displacement behavior of fasteners. A comparison of the statistics of the uplift capacity with and without the missing or improperly fastened nails is carried out. Also, the impact of considering and ignoring the missing or improperly fastened nails on the estimated reliability of roof panel under wind loading is presented. Furthermore, a sensitivity analysis is carried out by considering the fastening schedule recommended by the NBCC [20] and a more stringent fastening schedule.

2. Human error: the case of improper fastening of roof panels

A major contributing factor to structural failure is human error or construction error, which may be defined as "significant departure from standard practice" [21]. However, the quantification of the human error in practice is a complex task. In this section, the assessment of the human error in construction is very specific in that it focuses on the quality of the fastening of the plywood roof panel to the roof trusses. Missing nails (i.e., nails at specific locations are required but missing) and improperly fastened nails (i.e., nails that have penetrated to the roof panels but missed the roof trusses) are considered to be caused by human error.

The assessment of the statistics of the missing or improperly installed nails is carried out based on the information gathered from the construction of the full-scale test house at the IRLBH [17,18]. The house is a two-story wood frame house, shown in Fig. 1, with brick veneer that was built with standard building technology and normal construction procedure. The quality of construction, according to more than 20 local building inspectors, was representative of current industry standard. In other words, the quality of the construction of this "as-built" house is no better or no worse than that of a typical Canadian residential house. This two-story test house has plane dimension of 9.3 m × 9.3 m, an eave height of 5.2 m and a gable roof slope of 4:12. The ½ inch (nominal thickness 11.5 mm) plywood panels were used as roof panels; 8d common nails (with 63 mm (2.5″) length and 3.4 mm (0.133″) diameter) were installed using nail guns to fasten the panels to the roof trusses constructed of 2″ × 4″ lumber. The fastening schedule for the roof panels used is based on that recommended by the NBCC [20], which considers a nail spacing of 150 mm along the edge supports and 300 mm along the intermediate supports. Illustrations of the roof panel connection tolerance can be found in [22].

(a) Full scale test house during construction (processed to avoid commercial contains)

(b) Full scale house after installing brick veneer walls.

Fig. 1. The full-scale two-story test house.

The inspection and survey of the fastening for the roof were carried out immediately after the completion of the construction of roof panels and before the installation of shingles. Extensive photos of the roof top were taken, and the location of the nails along each roof truss was measured. Also, a survey of the adequacy of the fastening was conducted in the attic to see whether a nail appearing on the top of the roof panel had missed the roof truss. Nails that were not properly installed were identified by pairing the locations of nail heads and nails that missed the indented frame.

The information on the fastening obtained from the survey is shown in Fig. 2 and Table 1. Fig. 2 shows the locations of the properly installed nails as well as the improperly installed nails. It also shows the locations where nails are required but are missing. Note that if no human error is involved and the recommended fastening schedule in the NBCC [20] is followed, the number of the properly installed nails to fasten the roof panels is equal to 33 for a standard