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FINITE ELEMENT MODELING OF TIMBER I-JOISTS WITH WEB HOLES AND FLANGE NOTCHES

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Abstract: I-joists, studied in this research, are composite beams mainly used to support floor panels. They consist of oriented strand board (OSB) webs and timber flanges. For post-construction purposes, these beams are often drilled in the web or notched through the flange in order to pass electrical/mechanical facilities through. This can result in a significantly lower load-carrying capacity for these important elements. This study presents the finite element simulation of composite timber I-joists to predict the load-carrying capacity of these members with respect to size and location of the web hole and flange cut. Challenges involved in this study are reviewed, including the web-flange connectivity, numerical model meshing, computational precision and material properties. The numerical models are validated against experimental research and the data is used to obtain the load-deflection relationship for considered beams. It has been demonstrated that the proposed finite element simulation can perfectly capture the behavior of the beams. Furthermore, it is found that the existence of web holes or flange notches has considerable impact on the stiffness and load-carrying capacities.

Keywords: I-Joist; Web hole; Flange notch; Flange cut; Finite element analysis; Timber; Wood

1 Introduction

Wood has been a key construction material in North America and around the world (Kisternaya, Kozlov, Grishina, & Leri, 2016; Kouris & Kappos, 2014; Reynolds & Casagrande, 2016). It has gained constant attention due to its cost-effectiveness and lighter weight compared to other construction materials such as steel and concrete. Its availability and ease of use have given rise to its popularity, especially for short residential and commercial buildings.

I-joists, focused on in this research, are composite beams used mainly to support flooring and roof panels. They consist of oriented strand board (OSB) webs and timber flanges. The flanges are made of different wood species, as desired. Spruce-Pine-Fir, as an example, is a commonly used lumber for I-joist flanges in Canada and the United States. It is a combination of Canadian Spruces, Pines and Firs growing in different regions (Canada Wood Group, 2017). The combined web-and-flange configuration makes I-joists stronger in load-carrying capacity and lighter in weight, compared to solid timber sections. On the other hand, the space provided by their depth can be used for placing service conduits and ducts. However, to this end, they are often drilled in the web and/or cut through the flange to provide passageways. This action, in fact, can affect the structural integrity of the roof or flooring system, depending on the size and location of the cut. Since the top and bottom flanges can get highly stressed, notching of the flanges in the field has been restricted in a number of guidelines (American Wood Council, 1999). Despite this restriction, making cuts through I-joist web and flanges is quite often seen in practice, either inadvertently or because of limited space to pass building's electromechanical systems (Islam, Shahnewaz, & Alam, 2015; Shahnewaz, Islam, Ahmadipour, Tannert, & Alam, 2017; Shahnewaz, Islam, Alam, & Tannert, 2016). This fact highlights the importance to understand the behavior of cut I-joists under various loading scenarios.

Very limited research has so far been carried out on cut I-joists, amongst which many are focused on the effect of web holes rather than flange cuts (notches). As examples, Shahnewaz et al. investigated the presence of web holes in OSB webbed I-joists (Shahnewaz et al., 2017, 2016)They experimentally tested ten configurations of web holes with different sizes and locations in order to assess the capacity and failure modes. The uncut joists showed a flexural failure at the mid-span. On the contrary, a premature failure was observed in the beams with openings. It was reported that the capacity was reduced up to 54% in some cases. Moreover, they proposed a retrofitting procedure for the openings using which the premature failure can be prevented and the strength can be enhanced by 27%. Zhu et al., in a related study, have tested and modeled a series of I-joists with 9-mm OSB webs and Sitka spruce flanges with web openings (Zhu, Guan, Pope, & D, 2007). It is observed in their study that the failure starts from tension zones around the opening and continues to the flanges, which causes the joist to collapse. Two types of holes, square and circular, are considered and a generally similar pattern is found for both. Same researchers, in further studies, investigated the lateral buckling and local web buckling of such joists and the effect of interactions between multiple openings (Zhu, Guan, Rodd, & Pope, 2005, 2006).

On the other hand, very fewer researchers have investigated the effect of flange cuts on the performance of I-joists. Islam et al. have conducted an experimental study on about 100 I-joist specimens, investigating the load-carrying capacity and failure modes of 12- and 20-foot I-joists with ten different flange notch configurations (Islam, Shahnewaz, & Alam, 2015). They tested both size and location of the flange cut and observed that the load capacity can be reduced even up to 80% compared to control I-joists. Hindman and Loferski, from another point of view, proposed a retrofitting method using cold-formed steel sheets to reinforce the web and top flange in order for the cut I-joist to re-gain its original capacity (Loferski & Hindman, 2008). However, this study did not explore the capacity reduction due to the flange notch.

Despite the continued research being conducted in this field, no thorough understanding of the behavior of such I-joists yet exists and current design specifications lack clear-cut guidelines in this regard (Canadian Standards Association, 2014). A robust finite element analysis can pave the way to conduct comprehensive research in this field to develop practical design guidelines. The main objective of this study is to introduce such finite element analysis with reasonable computational effort in order to ease further studies on I-joists with web openings or flange notches, generally referred to as "cuts" in this manuscript. ANSYS finite element software is used to model full scale beams. The results of the simulations are then matched with those of experiments. A very good correlation is observed between the numerical and experimental results, which depicts that the models are capable of capturing the behavior of the I-joists with a high accuracy.

2 Scope and methodology

In this paper, the flexural performance of timber I-joists with web holes and flange notches is investigated through finite element simulations. This study follows the previous research in which more than 100 I-joist specimens were examined experimentally, whose results are published in (Islam et al., 2015; Shahnewaz et al., 2017, 2016). A robust and efficient finite element model is made and introduced, in order to eliminate the need for expensive and time-consuming experiments. The difficulties associated with this modeling, including geometry, material properties and web-flange interaction, are challenged. The sensitivity of the model to meshing size and element density distribution around the cuts is studied to make the analysis efficient and minimize the computational cost, without losing accuracy. A total of ten full-scale models are tested, whose results are validated against experimental data. The results presented in the following sections will be useful in practice to predict the performance of web-holed and flange-notched I-joists with cuts of different sizes and at different locations.

3 Reference experiments

A total of 180 I-joist specimens were experimentally tested. The specimens were produced and prepared in the facilities of AcuTruss Industries Ltd., Kelowna, Canada. They came in two span lengths of 12 and 20 feet, with web hole and flange notch configurations described in **Error! Reference source not found.**. The beams consist of a 9.5-millimeter oriented strand board (OSB) web and 63×38 millimetre No. 2 SPF laminated veneer lumber (LVL) flanges, as shown in Figure 1. The manufacturer has limited the span length of such cross-section to 20 feet (NASCOR, 2010). A simply-supported pin-roller condition was provided as end supports and, to control the lateral buckling, a number of 10 and 16 lateral supports were used for 12- and 20-ft joists, respectively. Two point loads were applied at 1/3 and 2/3 of beam's length to simulate bending, conforming to ASTM D5055. Test on each specimen was replicated 10 times in order to account for the errors and variabilities in the experiment. The applied force was measured by the pressure gauge of the test set-up and calibrated using device manufacturer's manual. Also, the deflection of the beam was measured using a digital extensometer and verified through video processing by means of three HD cameras located at 1/4, 1/2 and 3/4 lengths of the beam span. For details of the test set-up, please refer to (Islam et al., 2015).

Table 1. Specimen details

Length (ft)	Specimen Mark	Opening Type	Opening Size ($in.$ or $in.$×$in.$)	Opening Location* (ft)
12	12A	No Opening	-	-
	12B	Web Hole	8 3/8	5
	12C		8 3/8	4
	12D		6	5
	12E		4	5
	12F	Flange Notch	4×4	5
	12G		4×4	4.5
	12H		4×4	4
	12I		4×6	4.5
20	20A	No Opening	-	-
	20B	Web Hole	8 3/8	9
	20C		8 3/8	7
	20D		6	9
	20E		4	9
	20K	Flange Notch	4×4	9
	20L		4×4	8.5
	20M		4×4	8
	20N		4×6	8.5

*Opening location measured from mid-point of the beam to center of the opening

Figure 2 shows schematic configuration of beams with openings. In this figure, L is used to denote the length of the beam, and x_{WH} and x_{FN} represent the location of the web hole or the flange notch, respectively, measured from the mid-span of the beam. D_{WH} denotes web hole's diameter and L_{FN} and D_{FN} are used to show the length and depth of the flange notch, respectively.

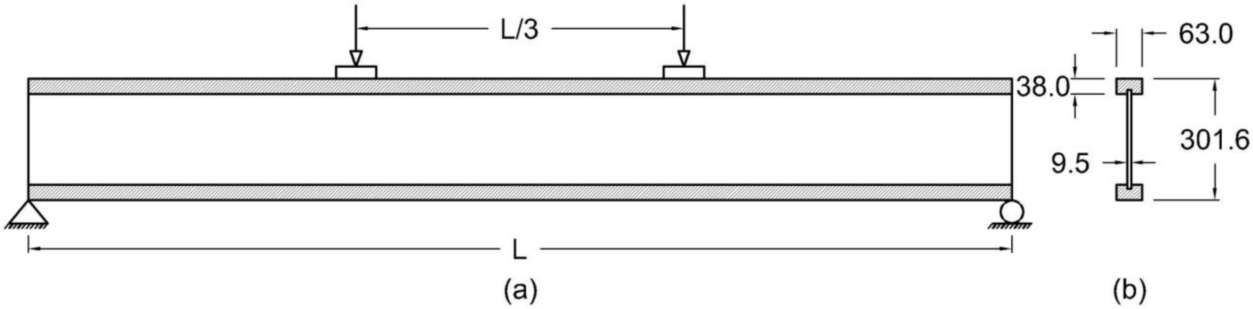

Figure 1. Schematic (a) side view and (b) cross-section of I-joists

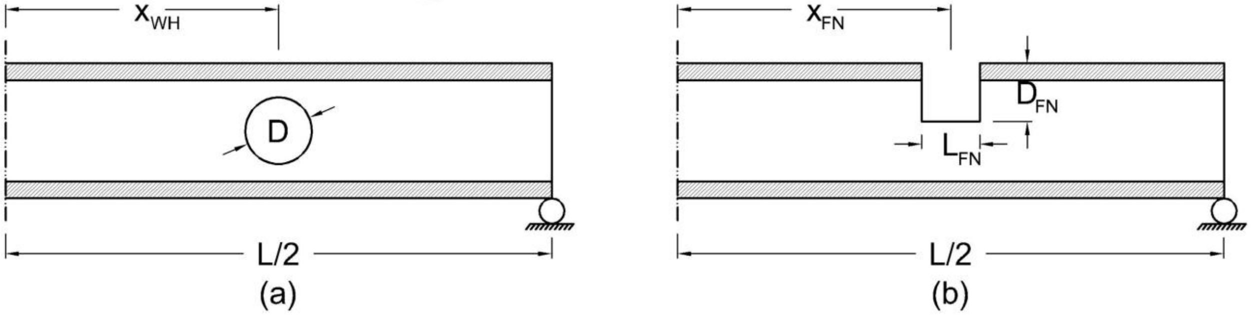

Figure 2. Schematic drawing of beams with (a) web openings and (b) flange notches

4 Finite element modeling

Despite the large number of specimens being tested, some limitations still exist in the experimental research. This is mainly because of the limitations on the number and cost of specimens and includes considering the effect of various sizes of web holes and flange notches, the location of the cuts and the interaction between them. Furthermore, the real loading condition, a uniformly-distributed load, cannot be tested experimentally effortlessly. The numerical study presented in this section is pursued in order to pave the way to address these issues with less cost. Mechanical APDL tool in ANSYS finite element program (ANSYS Inc, 2012) is implemented for this purpose and to produce more data to add to the experimental ones. Detailed three-dimensional finite element models of the tested I-joists are developed in order to capture their load-carrying performance. Figure 3 shows sample developed models for full-scale 12-ft I-joist with web hole and flange notches. Light blue color represents the OSB material and purple represents the flanges made of timber.

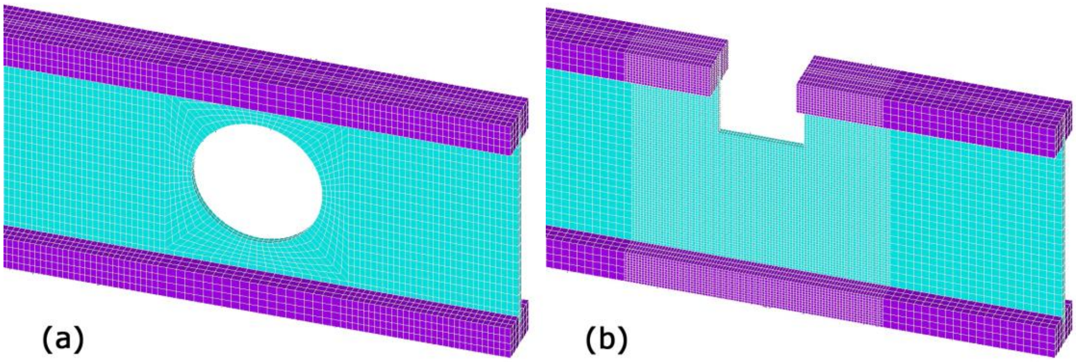

Figure 3. Finite element model of 12-ft (a) web-holed and (b) flange-notched I-joists

4.1 Material model

An anisotropic elastic material model is chosen to capture the behavior of both web and flange components. Tensile tests were used to determine the properties of OSB and timber in different directions. The elastic coefficient matrix is then constructed using material properties and input to the finite element software.

4.2 Geometry and connectivity

Full-scale experimented I-joists were modeled in real dimensions. SOLID 64 element is used to model joist parts, which is capable of capturing the anisotropy in solid structures (ANSYS Inc, 2006). This element possesses three degrees of freedom in the form of nodal translations at each of its eight nodes. It is a good choice to model wood with, since it can undergo large deflections. The geometry and dimensions are so chosen that they match real-scale I-joists. The connectivity between the web and flanges is considered to be a perfect bonding. This phenomenon is proved by verifying the results of the FE simulation against experimental ones, shown later in this text.

4.3 Loading and boundary conditions

In order to be able to validate the finite element model with the experiments, the loading and boundary conditions are set to represent real test scenarios. The exact two-point bending loading used in the experiments was simulated. The loads act at 1/3 points of beam’s length, transferred over a 4-inch bearing plate to distribute the pressure and avoid stress concentration. A simply-supported ends condition is introduced by constraining the movement of support nodes in vertical direction at both supports and prohibiting the movement of only one support in longitudinal direction of the beam. Lateral movements are prevented using 10 lateral supports for 12-ft and 16 for 20-ft specimens at both faces of the joist. These supports play a significantly important role, as they prevent the torsion in cut beams. Cut beams, specifically those with flange notches, are highly susceptible to torsion due to the stiffness asymmetry in longitudinal direction.

4.4 Mesh

Because of the large size of the specimens, meshing is an important challenge in this study. If not appropriately created, it can result in an expensive simulation in terms of time and computational efforts. In our finite element study, we conducted a sensitivity analysis in order to find out the appropriate element distribution leading to acceptable results explained in section **Error! Reference source not found.**. It is important to have adequately dense meshes in regions susceptible to stress concentrations, such as web hole and flange notch areas. Figure 4 shows the details of the meshing in these areas. A meshing block with adjustable size is created around the cuts in order to control the mesh density in this region and relate them to the coarser surrounding mesh. This method has helped to capture the full behavior of the sensitive regions, while saving computational costs in other regions. Another significant step in reducing the number of elements was introducing a symmetry condition at the middle plane of the beam, which cuts the computational efforts to half. This means the nodes on the symmetry plane have zero displacement normal to the plane – in Z direction, in our model. For all parts, mapped meshing with an ordered pattern is implemented, which makes the model more consistent.

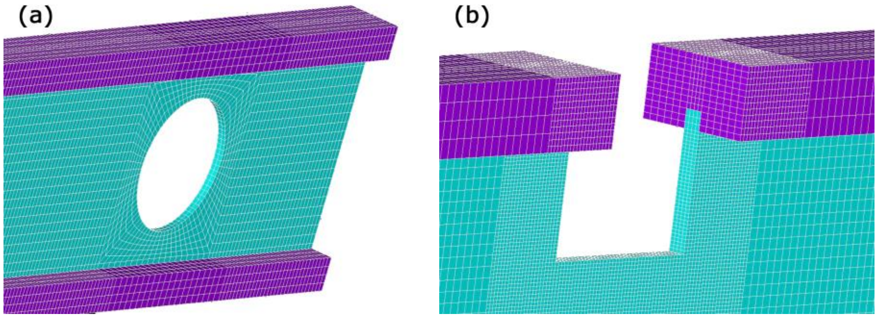

Figure 4. Meshing and element distribution around (a) web holes and (b) flange notches

5 Validation of results

Ten specimens of the experimental study described in Table 1 were selected to validate the numerical study. To this end, these specimens were modeled with all details according to simulation specifications described in section 4. The numerical models were subjected to bending loads identical to those in the experimental study, shown in Figure 1. The deflection of the joist is measured at the center point of the beam, at the mid-span. It is obtained by averaging the vertical displacements of nodes located within one inch of the mid-span. The analysis has been continued to the maximum deflection observed in the experiments, in order to capture the full response. Figure 5 and Figure 6 illustrate the load-deflection curves for 12-ft and 20-ft specimens, respectively. An excellent match is observed between the experimental and numerical results, which shows the robustness of the proposed simulation approach.

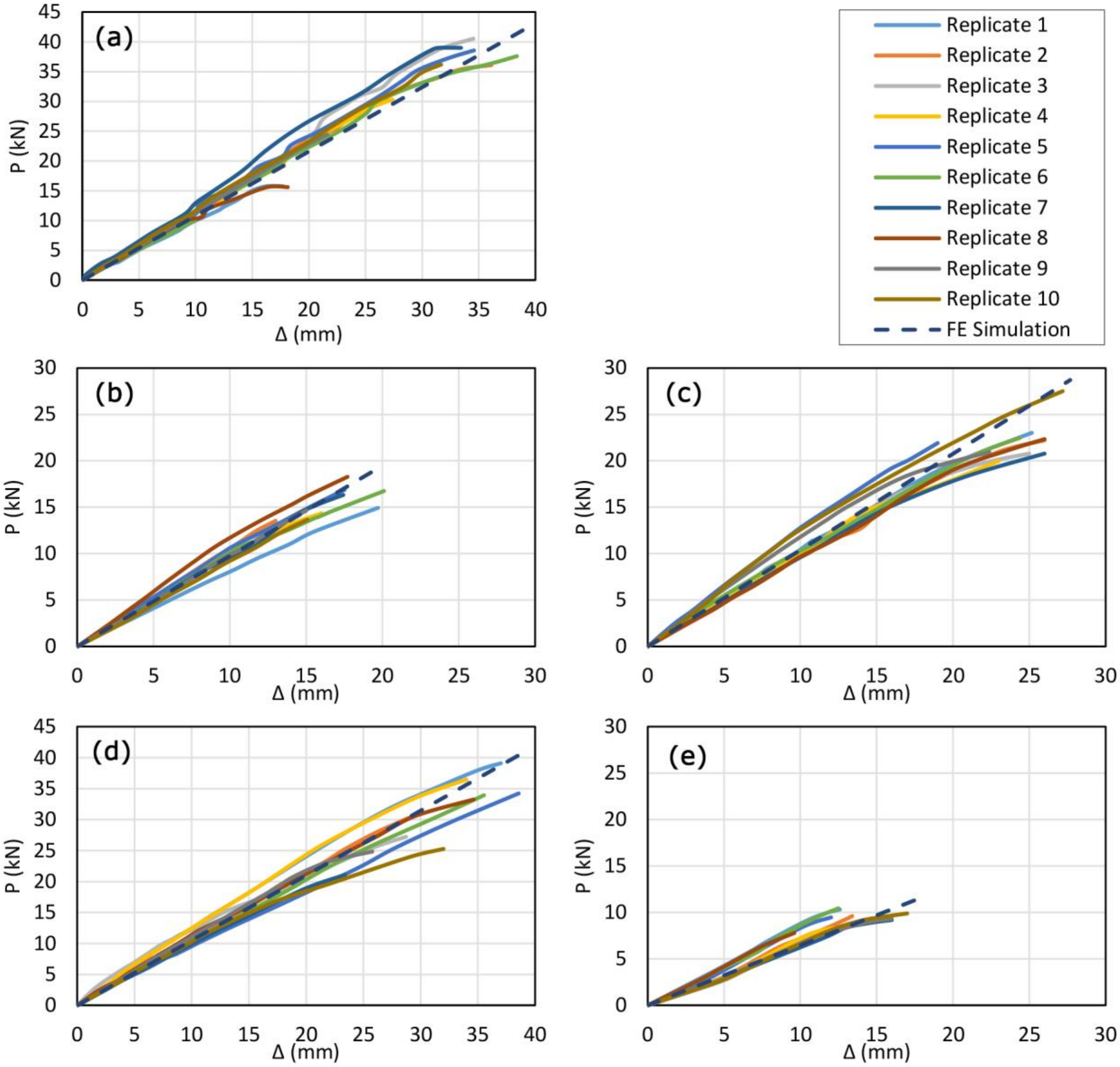

Figure 5. Load-deflection curves for specimens (a) 12A (control joist), (b) 12B, (c) 12D, (d) 12E and (e) 12I

6 Conclusions

A finite element model is proposed for modeling composite timber I-joists with OSB web and timber flange notches. Ten experimentally tested I-joists are modelled using Mechanical APDL tool in ANSYS finite element program. The load-displacement responses have been obtained and the results have been validated against those of experiments. A very close collaboration has been observed, confirming the accuracy of the proposed model. Based on the research conducted, the following conclusions are drawn:

- The material properties obtained and material model used were able to accurately predict the behavior of OSB and timber in bending.
- The proposed finite element modeling approach is capable of capturing the behavior of OSB-webbed timber I-joists within a very small tolerance, validated against experimental studies.
- The meshing strategy, having a denser distribution near the cuts and looser divisions in less important areas, was an efficient method to significantly reduce the computational efforts.
- The proposed finite element approach is valid and accurate to be used for predicting the behavior of timber I-joists with any web hole and/or flange notch configuration.

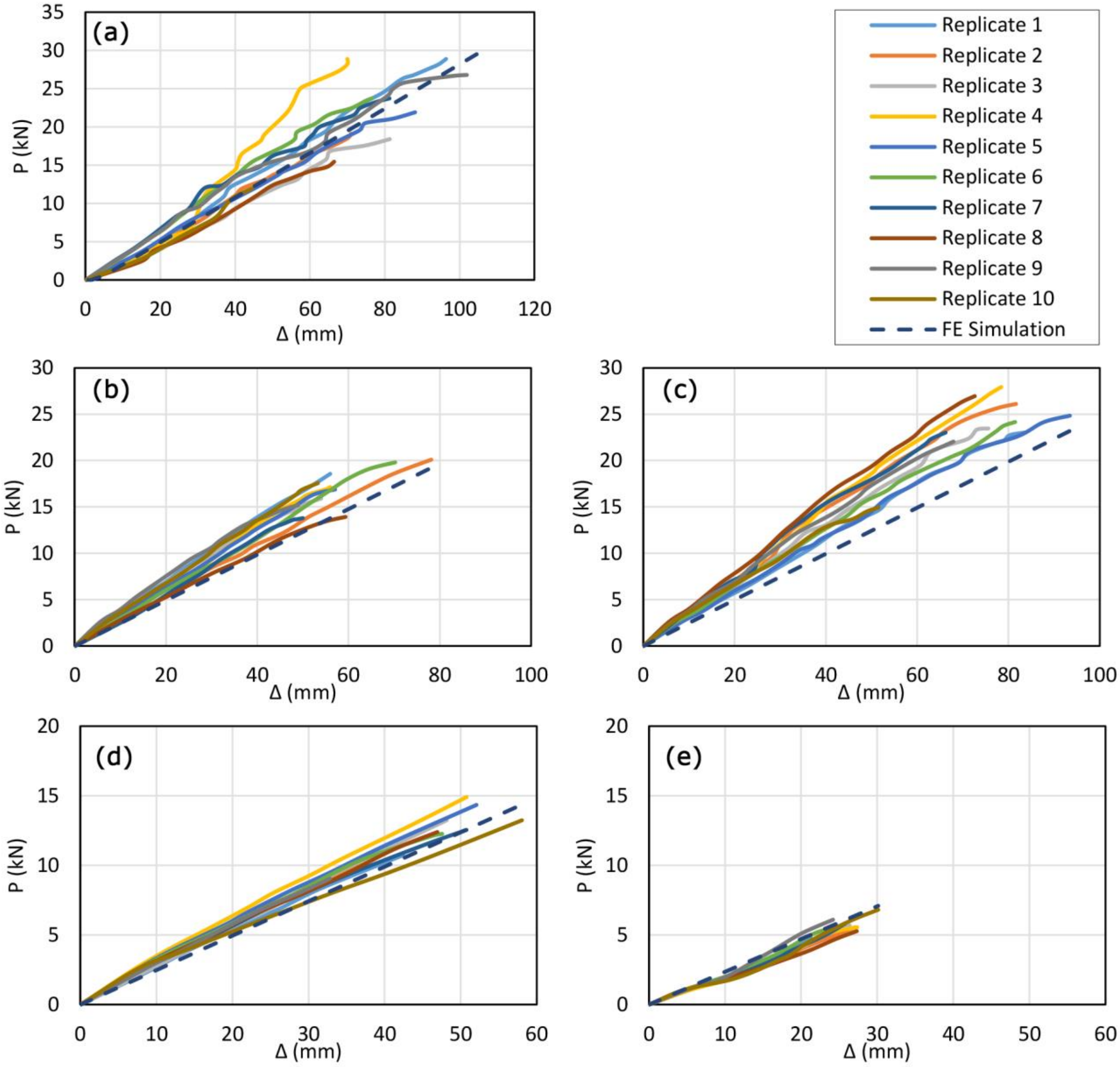

Figure 6. Load-deflection curves for specimens (a) 20A (control joist), (b) 20C, (c) 20D, (d) 20K and (e) 20N

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