



## DESIGN CONSIDERATIONS FOR CROSS-LAMINATED TIMBER PANELS SUBJECTED TO SIMULATED BLAST LOADS

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**Abstract:** This paper presents the results from an experimental program investigating the out-of-plane behaviour of cross-laminated timber (CLT) panels under static and simulated blast loading. A total of eighteen CLT panels were investigated with the aim to determine the dynamic behaviour of CLT panels. Dynamic testing was conducted through the use of simulated blast loads produced by a shock tube testing apparatus. An average dynamic increase factor (DIF) on the resistance is developed. Two material predictive models are proposed, which take into consideration high strain rate effects, failure modes, and the experimentally observed post-peak residual properties. A single degree-of-freedom (SDOF) model was validated using full-scale simulated blast load test results, and the predictions were found to match well with the experimental displacement-time histories. Current Canadian Blast Design Standard provisions were found to provide relatively conservative and accurate predictions when using the proposed DIF and analytical model.

### 1 INTRODUCTION

Cross-laminated timber (CLT) panels consist of lumber boards stacked in layers which run perpendicular to one another. The end product is dimensionally stable with high in- and out-of-plane strength and stiffness. Recent interest in sustainable construction has led to an increase in the use of heavy- and mass-timber elements, particularly CLT. The usage of wood beyond that of low-rise construction has been very limited primarily due to code requirements that are outdated and prescriptive in nature. The use of wood in tall (e.g. UBC Brock Commons) and high profile (e.g. Richmond Olympic Oval) buildings has also meant that such buildings may be exposed to heightened risk, including that stemming from intentional or unintentional blast loading.

Blast loading occurs during an extremely brief time period, generating high strain rates in the materials exposed to the loading. This short duration loading affects the mechanical properties of the material and an apparent increase in strength relative to the material's static strength is typically observed. This increase is quantified as the ratio of the dynamic to the static strength, termed "dynamic increase factor" (DIF). DIFs for different materials can be found in various blast design codes (ASCE 2011, CSA 2012).

Several studies have investigated CLT's material properties, specifically relating to rolling shear (Flores et al. 2016, Li and Lam 2016, Zhou et al. 2014), as well as the behaviour of CLT when subjected to out-of-plane loads (Jacquier 2015, Sikora et al. 2016, Steiger and Gülzow 2009), in-plane loads (Ashtari et al. 2014, Ceccotti et al. 2006, Popovski and Gavric 2016, Yasumura et al. 2016), and fire (Fragiacomo et al.

2013, Frangi et al. 2009, Frangi et al. 2004). However, research is lacking in the area of establishing the behaviour of CLT under hazardous and short-duration loads, such as that arising from blast loading. Understanding the behaviour of CLT when subjected to such loads is imperative in the development of harm-mitigation strategies which focuses on occupant life safety and progressive collapse prevention.

The majority of studies on DIF have been on reinforced concrete (e.g. Barreiro 2016, Burrell 2012, Jacques 2011, 2016, Lloyd 2010) and structural steel (e.g. Jama et al. 2009, Nassr et al. 2012) members, due to their inherent blast-resistant properties. Studies on bare studs (Jacques et al. 2014) and light-frame wood stud walls (e.g. Collins and Kasal 2009, Lacroix and Doudak 2015, Lacroix et al. 2014, Marchand 2002, Viau 2016, Viau and Doudak 2016b) have shown a significant increase in the flexural strength when subjected to high strain rates. A recent project investigated whether CLT buildings would meet the United States Department of Defense level of protection requirements (Senalik and Podesto 2017). The results from these live blast tests show that desired levels of protections can be achieved with CLT, however, little details have been made available to the public, including whether a DIF was observed during testing.

The goal of this paper is to investigate the out-of-plane behaviour of CLT panels under static and blast loading. The development of the material-predictive model will first be summarized and used to develop a generalized code-based design approach of one-way CLT panels. The code-based approach will then be validated using the experimental test results.

## 2 EXPERIMENTAL PROGRAM AND RESULTS

A recent study conducted at the University of Ottawa on eighteen spruce-pine-fir CLT panels focused on quantifying high strain rate effects in CLT (Poulin et al. 2017). The width and the length of all panels were 445 mm and 2,500 mm, respectively, with thicknesses of 105 mm and 175 mm (i.e. 3-ply and 5-ply). The study consisted of static and dynamic testing phases, during which the properties were experimentally obtained.

### 2.1 Static Testing Phase

The static tests consisted of subjecting the panels to four-point bending with simply supported boundary conditions until failure was obtained. Through a hydraulic jack, loading was applied at a rate which would induce failure at a time between 2 and 10 minutes. The applied load, mid-span deflection, and compressive and tensile strains were measured at a sampling rate of 10 samples per second. Of the eighteen panels, six were tested to destruction and twelve were tested within their elastic range in order to determine their stiffness. This information was used as input in modelling the blast behaviour of each panel. The results of the static testing phase are summarized in Table 1, which includes the mean and coefficient of variation (CoV) of the maximum resistance, ductility ratio, initial stiffness based on experimental load resistance curve from 10 to 40%, and the experimentally observed post-peak resistance expressed as a percentage of the maximum resistance.

Table 1: Results of Static Testing

Specimen Group	Max. Resistance		Initial Stiffness		Ductility Ratio		Post-Peak Resistance	
	Average (kN)	CoV	Average (kN/mm)	CoV	Average	CoV	Average (%)	CoV
3-ply	68.4	0.08	2.1	0.01	1.8	0.11	20	0.09
5-ply	128.6	0.03	5.9	0.03	2.2	0.19	20	0.15

For both CLT panel groups, a linear relationship up to the maximum resistance was observed at which outer longitudinal lamination failure occurred, as shown in Figure 1 (a). Resistance plateaus were observed past the maximum resistance, which correlated to the resistance of the residual undamaged section of the panel. Superimposing a typical 5-ply panels' resistance curve over that of a 3-ply (Figure 1 (b)), it can be seen that the first drop in resistance of the 5-ply panels corresponds to the ultimate strength of a 3-ply panel.

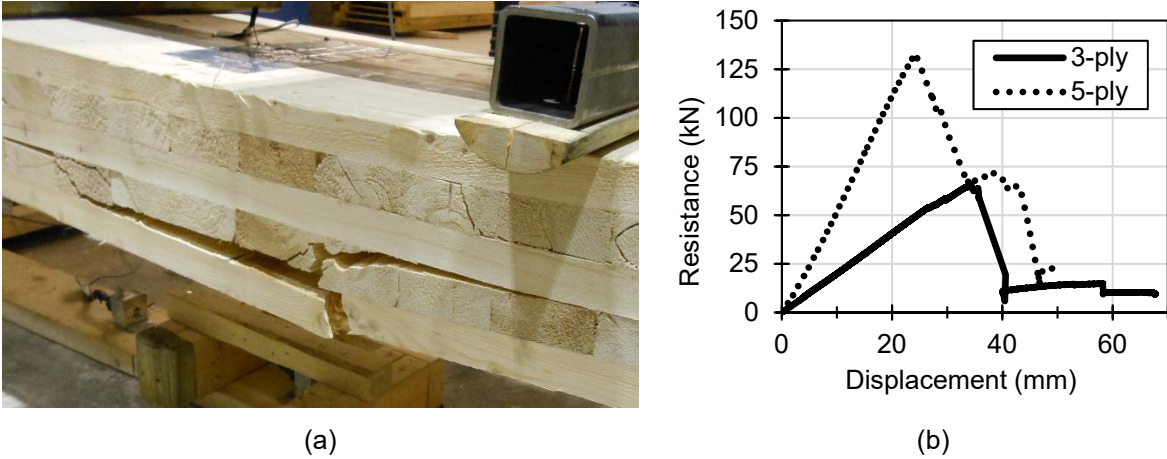


Figure 1: (a) Typical static flexural failure; (b) Typical experimental static resistance curves

**2.2 Dynamic Testing Phase**

Through the use of a shock tube, twenty simulated blast loads were applied to the twelve specimens that were tested non-destructively during the static testing phase. This method of generating high strain rates on structural components has been widely used in past studies and accepted as an effective methodology to generate blast loads in timber and reinforced concrete elements (Jacques et al. 2015, Lacroix and Doudak 2015, 2018, Viau and Doudak 2016a) as well as fibre reinforced structural elements (Aoude et al. 2015).

Four-point bending was used in the dynamic testing in order to allow direct comparison of resistance and stiffness with those obtained through static testing. Pressure waves were collected and transferred to the specimens via a load-transfer device (LTD), which converted the blast loading to two concentrated loads at the third points. Load-cells were placed at the specimen support points in order to measure the dynamic reactions. The reactions in addition with the applied loads and inertial forces of both the specimen and LTD were used in the calculation of the dynamic resistance-displacement relationships for each test specimen, according to dynamic equilibrium (Biggs 1964). The dynamic response was documented through the use of a data acquisition system recording 100,000 samples per second, as well as high-speed camera. A summary of the dynamic results for the panels is presented in Table 2.

Table 2: Results of Dynamic Testing

Specimen Group	Max. Resistance		Initial Static Stiffness		Ductility Ratio	
	Average (kN)	CoV	Average (kN/mm)	CoV	Average	CoV
3-ply	83.7	0.04	1.9	0.10	2.7	0.14
5-ply	174.2	0.01	5.4	0.05	2.3	0.11

Whereas flexural failure was the primary failure mode observed during static testing, some specimens under dynamic loading experienced significant rolling shear. An example of such rolling shear failure is shown in Figure 2 (a). Due to the early onset of rolling shear failure, the longitudinal laminates deflected almost as individual elements rather than a composite section, causing a degradation in stiffness. The loss of stiffness meant that the specimen could deflect much more and return to its original position. In cases where dynamic flexural failures were observed, they were similar to those observed during static testing, with little to no significant rolling shear failure, as seen in Figure 2 (b). Panels where rolling shear damage was documented following a shock tube test were later tested statically in order to determine their residual stiffness. It was found that the degraded stiffness of these panels varied between 20 to 35% of that observed in their undamaged condition.

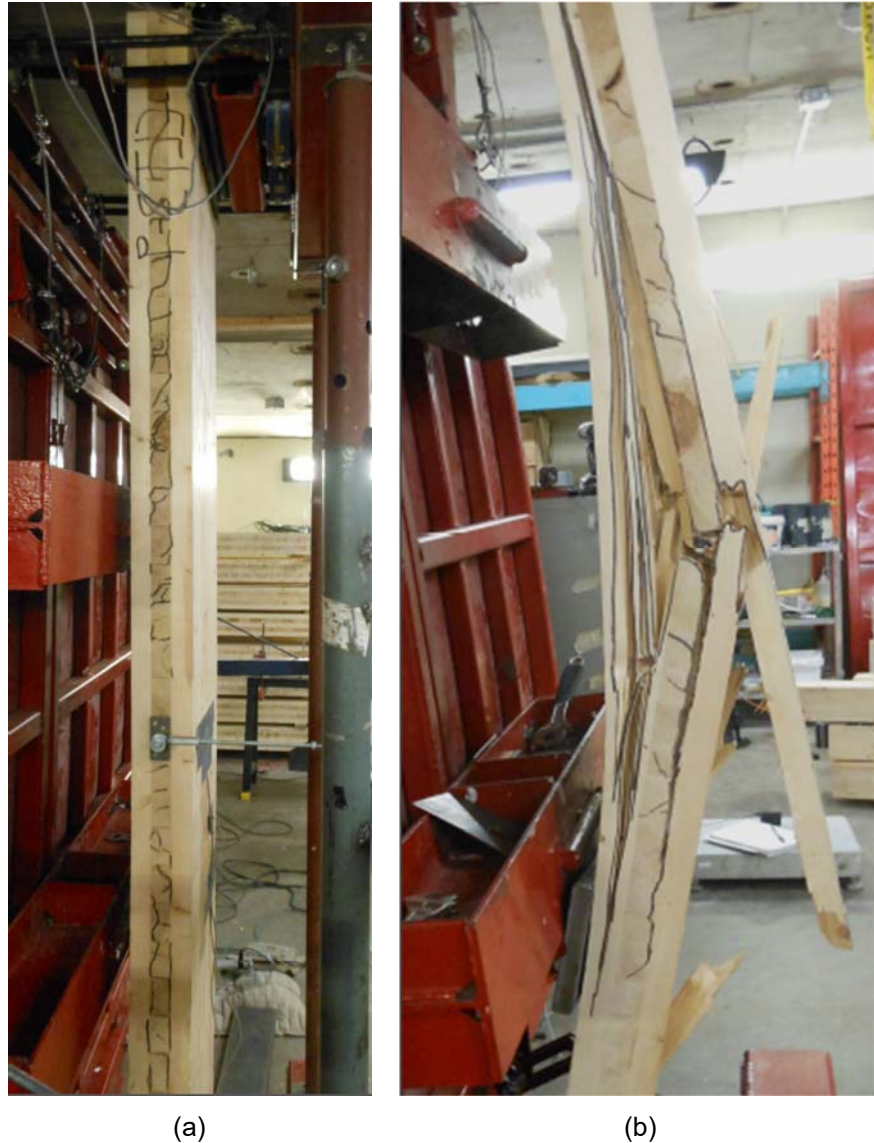


Figure 2: Representative dynamic: (a) Rolling shear failure; (b) Flexural failure

### 2.3 Dynamic Increase Factor

Experimentally obtained static and dynamic resistance-displacement relationships showed an increase in strength when subjected to high strain rates, while no increase was observed in the stiffness. An average dynamic increase factor (DIF) of 1.28 was determined from comparing the static and dynamic testing results (Poulin et al. 2017).

## 3 DEVELOPMENT OF A MODELLING APPROACH FOR CLT

Based on the experimentally obtained resistance curves, a generalized approach for constructing the resistance curve of both 3-ply and 5-ply specimens was developed, for both failure modes observed – namely flexure and rolling shear failure (Poulin et al. 2017).

The flexural behaviour of both specimen groups can be described as initially linear elastic, after which the loss of the bottom longitudinal laminates would cause a sudden drop in resistance. For the 3-ply specimens,

this post-peak behaviour was modelled as a sudden drop in resistance to a value equal to 20% of the ultimate resistance. The value of 20 % was determined by experimental testing. For the 5-ply specimens, the loss of the outermost laminates means that the specimen would now behave as a 3-ply specimen. At a deflection equal to that of the elastic limit of the equivalent 3-ply, the resistance curve would drop to a value equal to approximately 20% of the ultimate resistance of the 5-ply specimen, which is consistent with the approach for the 3-ply specimens. The post-peak residual deflections were capped at a maximum ductility ratio of 2.5, based on the experimental findings. Representative flexural resistance curves are shown in Figure 3 (a) for the 3- and 5-ply specimens.

Specimens in which rolling shear failure occurred prior to any flexural failure necessitated a modified approach to capture this behaviour. When rolling failure is fully developed, the section no longer behaves as one rigid component, but rather as a set of (undamaged) longitudinal laminates weakly connected by the transverse laminates which have become heavily damaged by rolling shear. The partial composite action between the laminates caused a significant reduction in stiffness (on the order of 65-80% reduction). An example of a resistance curve modified for rolling shear failure is shown in Figure 3 (b).

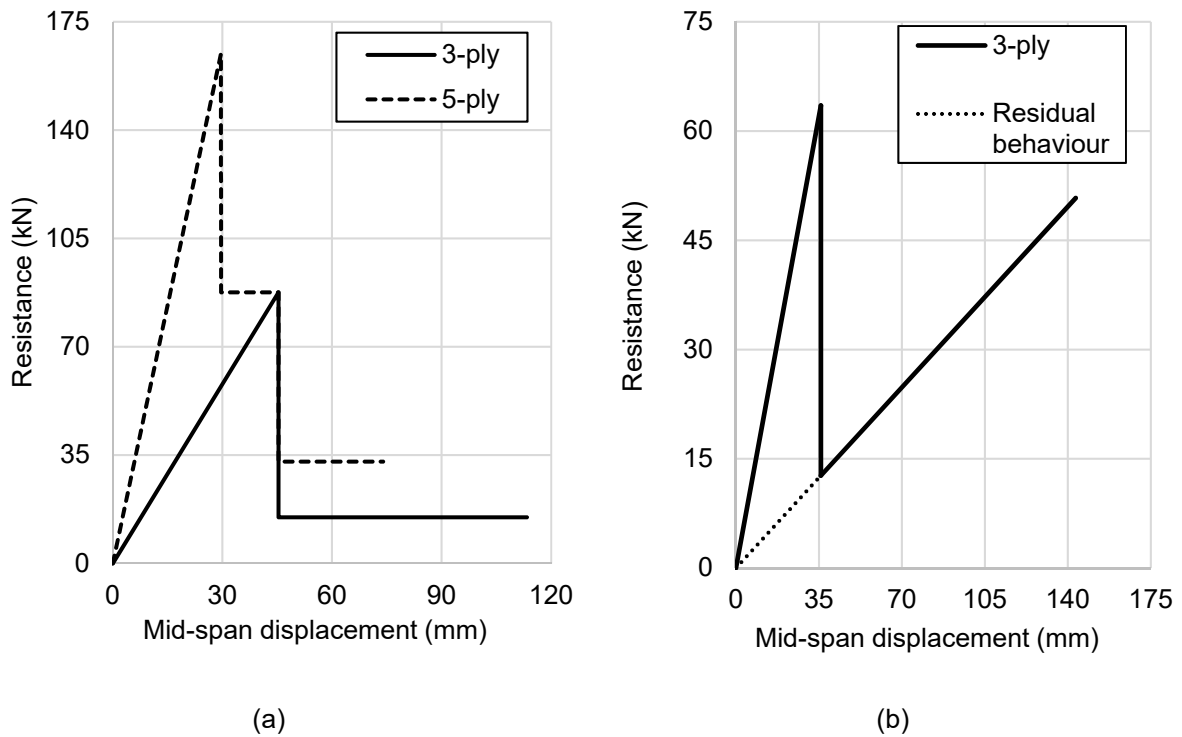


Figure 3: Representative resistance curves: (a) flexural failure; (b) rolling shear failure

#### 4 PROPOSED DESIGN APPROACH

Current blast provisions provide designers with the means to conduct blast analysis and design for various materials, including wood structures (ASCE 2011, CSA 2012). Blast analysis is currently based on establishing a desired level of protection (LOP) to which an element can be assessed. Once established, this methodology is used in determining whether the quantifiable response and overall damage level meet the desired LOP. The basis of blast design consists of increasing design-level capacities to mean values, with additional consideration for high strain rate effects. This adjustment is done through the use of a strength increase factor (SIF) and a dynamic increase factor (DIF). The ultimate dynamic moment capacity and resistance are calculated using Equations 1 and 2, respectively.

$$[1] M_{dyn} = \Phi \cdot SIF \cdot DIF \cdot M_{static}$$

$$[2] R_u = 6 \cdot M_{dyn} \cdot L^{-1}$$

where  $\Phi$  is the material adjustment factor, which is set to unity for blast, SIF is the strength increase factor, DIF is the dynamic increase factor,  $M_{static}$  is the specified static moment strength obtained from manufacturer tables (kN·m), and L is the clear span (m).

The Canadian blast standard currently assigns a SIF of 1.2 for glulam and engineered wood products (CSA 2012). This value is consistent with the adjustment factor of 1.25 provided in CSA O86 for stress grade E1 CLT panels (CSA 2014) and is in line with what was observed in this study (1.24). A DIF of 1.28 was found to be appropriate for CLT based on findings from the experimental program. The stiffness of a CLT panel subjected to third point bending is calculated using Equation 3 (ASTM 2015).

$$[3] K = (L^3 \cdot (56.4 \cdot EI_{eff})^{-1} + \kappa \cdot L \cdot (5 \cdot GA_{eff})^{-1})^{-1}$$

where L is the clear span (m),  $EI_{eff}$  is the effective bending stiffness (kN·m<sup>2</sup>),  $GA_{eff}$  is the effective shear rigidity (kN), and  $\kappa$  is the shear coefficient factor, equal to 1.2 for rectangular sections (Timoshenko and Woinowsky-Krieger 1959).  $M_{static}$ ,  $EI_{eff}$ , and  $GA_{eff}$  are obtained from published manufacturer tables.

The elastic limit, denoted  $x_e$  (m), for both panels is calculated by dividing the resistance by the stiffness obtained from Equations 2 and 3, respectively. The inputs used in calculating the resistance curves are presented in Table 3.

Table 3: Modelling inputs based on published *Nordic Structures*® design data

Panels	SIF	DIF	$M_{static}$ (kN·m)	$EI_{eff}$ (kN·m <sup>2</sup> )	$GA_{eff}$ (kN)	$R_u$ (kN)	K (kN/m)	$x_e$ (m)
3-ply	1.2	1.28	18.8	481.0	3248.5	77.5	1734	0.045
5-ply	1.2	1.28	43.0	1842.3	6675.0	177.4	5324	0.033

Shown in Figure 4 are the resulting resistance curves for the 3-ply and 5-ply panels based on published data assuming flexure model only. The rolling shear model presented in this paper can be used if a designer is able to predict this failure mode with some level of certainty. Although lower stiffness at the early stages of loading would cause higher displacements, this displacement cannot directly correlate to significant damage when compared to panels that failed in flexure. It was therefore decided that for the purpose of illustrating a simplified design approach, only the flexure model would be considered, as it represents the more critical of the two failure modes.

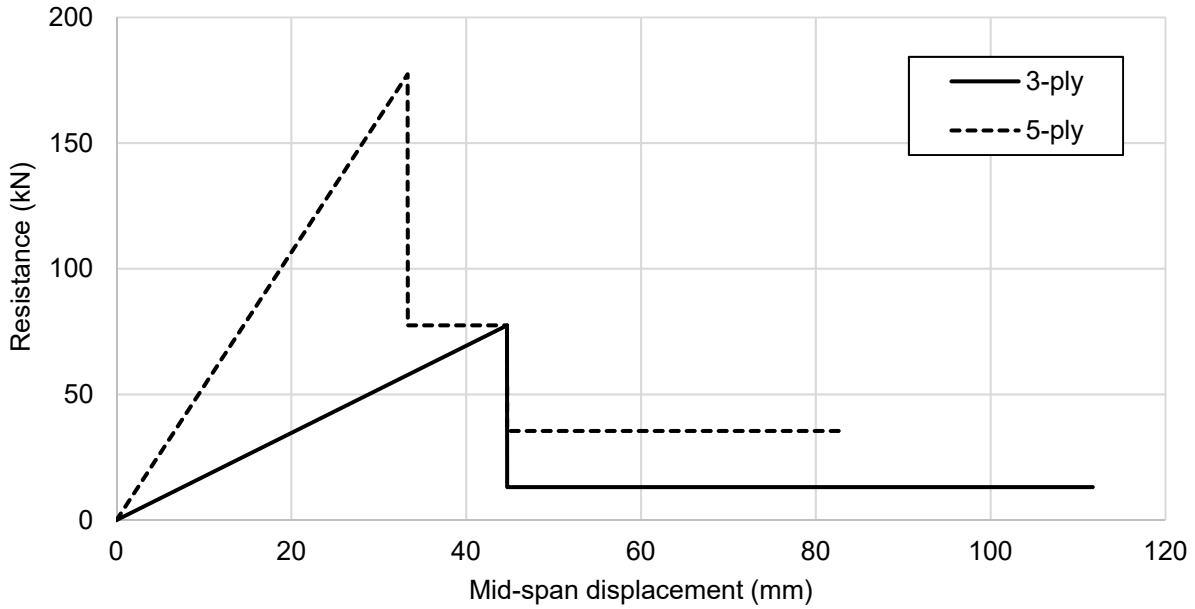


Figure 4: Resistance curves based on published strength modified using code-based SIF and experimental DIF

The analytically predicted displacements against those experimentally obtained is presented in Figure 5. The prediction of the model seems reasonable on average, with the model based on published data over predicting displacements on average by 1 %. Based on these results, it can be concluded that conducting blast analysis based on published static values modified for the published value of SIF (1.2) and the obtained DIF value (1.28), while assuming flexural failure seems to predict the displacements of CLT panels with reasonable accuracy.

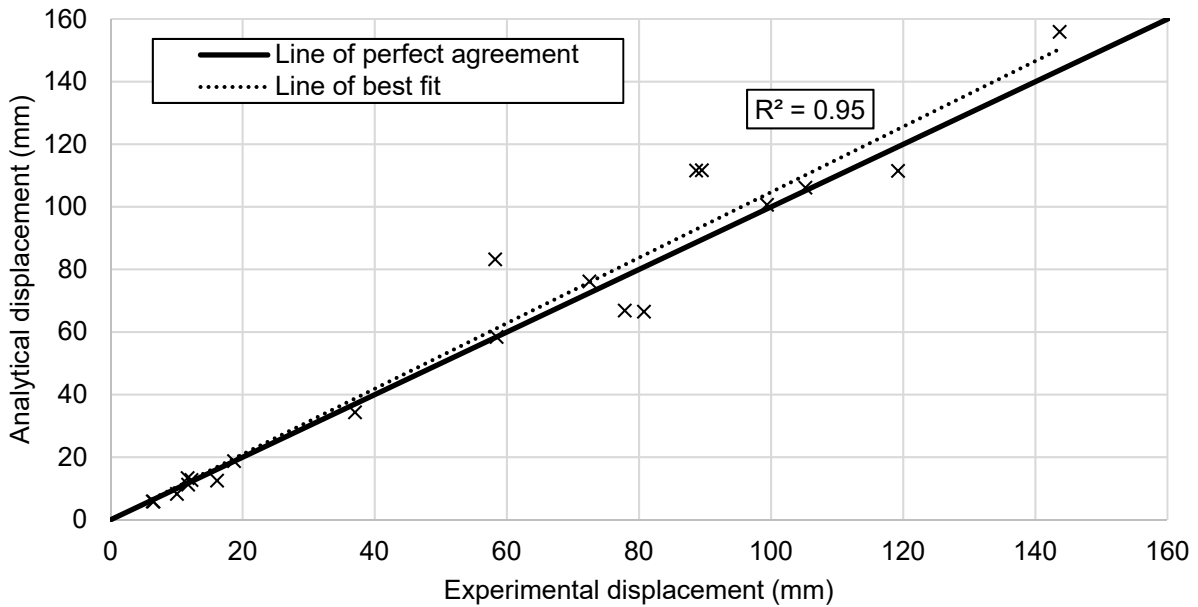


Figure 5: Comparative view of analytical and experimental displacements – code approach

## 5 CONCLUSIONS

An experimental investigation to determine the static and dynamic behaviour of cross-laminated timber panels was undertaken. An average dynamic increase factor of 1.28 on the resistance was determined, while the dynamic stiffness did not seem to be affected by the increase in strain rate. Residual post-peak resistances were observed in both static and dynamic test, and a modelling approach which incorporates these residual resistances was successfully used. A single degree-of-freedom model utilizing material properties and observed behaviour was developed and validated with experimental dynamic test results. Reasonable correlation between predicted and experimentally obtained panel displacements was found when assuming flexural failure and while modifying the static strength with a SIF and DIF.

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