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Development of Ductility-related Force Modification Factors for CLT Structures in Canada

Maria Koliou[1], John W. van de Lindt[2], Marjan Popovski[3]

[1] Assistant Professor, Texas A&M University, College Station, TX, USA.
[2] Harold H. Short Endowed Chair Professor, Colorado State University, Fort Collins, CO, USA.
[3] Principal Scientist, FPInnovations, Vancouver, BC, Canada.

ABSTRACT

Although steel and reinforced concrete are the two main materials that have been used extensively and exclusively in the construction of high-rise buildings for the last century, the need for a sustainable material with a lower carbon footprint has never been more apparent. Global warming and climate change, in general, has shifted the attention of engineers towards design of wood structures that use Mass Timber products such as Cross Laminated Timber (CLT). A number of mid-rise and high-rise timber buildings have been built in Europe and elsewhere over the last decade and their number is expected to grow in the years to come. The use of CLT as a Seismic Force Resistant System (SFRS) in North America has been somewhat limited so far due to the lack of design guidance in the Canadian and US codes and standards. The objective of this study is to identify an appropriate ductility-related force modification factor (R_d) for the seismic design of platform-type CLT SFRS for implementation in the National Building Code of Canada (NBCC). A set of representative archetype configurations of various aspect ratios, building heights and seismic design categories are considered in this study. Numerical models of the various building configurations designed with different R_d-factors were generated and non-linear response analyses were conducted in a manner similar to the U.S. Federal Emergency Management Agency (FEMA) P695 collapse assessment methodology under a representative suite of input ground motions accounting for different sites across Canada, including Victoria, Montreal, Burnaby BC, and Alma, QC. The results of this study may be used to propose an R_d-factor suitable for the seismic design of platform-type CLT buildings in Canada accounting for uncertainties in modeling, design, testing and ground motions as per FEMA P695 guidelines.

Keywords: Cross Laminated Timber; Incremental Dynamic Analysis; Ductility-related Force Modification Factor.

INTRODUCTION

Although steel and reinforced concrete are the two main materials that have been used extensively and exclusively in the construction of high-rise buildings for the last century, the need for a sustainable material with a lower carbon footprint is apparent. Global warming and climate change in general has shifted the attention of engineers towards design of wood structures that use Mass Timber products such as Cross Laminated Timber (CLT). A number of mid-rise and high-rise timber buildings have been built in Europe and elsewhere over the last decade and their number is expected to grow in the years to come. However, the use of mid- to high-rise CLT buildings so far has mainly been observed in low- to moderate seismic regions. The use of CLT as a Seismic Force Resistant System (SFRS) in North America has been somewhat limited so far due to the lack of design guidance in the Canadian and US codes and standards. There are currently research efforts in the United States focusing on the design, seismic performance and assessment of tall CLT buildings subjected to extreme seismic loads (e.g., [1, 2]). In this study, the focus is on identifying and evaluating an appropriate ductility-related force modification factor (R_d) for the seismic design of platform-type CLT as a SFRS for future implementation in the National Building Code of Canada (NBCC). This is performed in this study by applying the FEMA P695 collapse assessment methodology for a limited set of representative archetype configurations of various aspect ratios, building heights and seismic design categories.

FEMA P695 METHODOLOGY OVERVIEW

The FEMA P695 methodology [3] provides a rational basis for evaluating existing and new seismic force resisting systems and their ability to meet the seismic performance intent of the design provisions. The methodology involves advanced nonlinear dynamic analysis techniques and explicitly accounts for uncertainties in ground motions, modeling, design and test data in the probabilistic assessment of collapse risk.

This methodology is consistent with the "life safety" performance objective required by the seismic regulations. This objective is achieved by enabling a low probability of collapse of the seismic force resisting system when subjected to ground motions at the MCE intensity level. The FEMA P695 methodology addresses partial and global structural collapse of the seismic force resisting system without accounting for local component failures.

The main steps comprising the FEMA P695 methodology are:

- *Step 1-Obtain Required Information*: Required system information includes detailed design requirements and results from material, component and system testing.
- *Step 2-Characterize Behavior*: Characterizing system behavior includes development of index archetype configurations and identification of performance groups.
- *Step 3-Develop Models*: Development and validation of nonlinear models accounting for the design requirements and test data provided.
- *Step 4-Analyze Models*: Nonlinear static and dynamic analyses conducted using the FEMA P695 Far-Field ground motion ensemble.
- *Step 5-Evaluate Performance*: The collapse performance of the structural system is evaluated by following certain process to ensure low probability of structural collapse.
- *Step 6-Document Results*: Documentation of all design considerations, modeling assumptions and evaluation/analysis results

The flowchart of Figure 1 presents schematically the process of the FEMA P695 methodology.

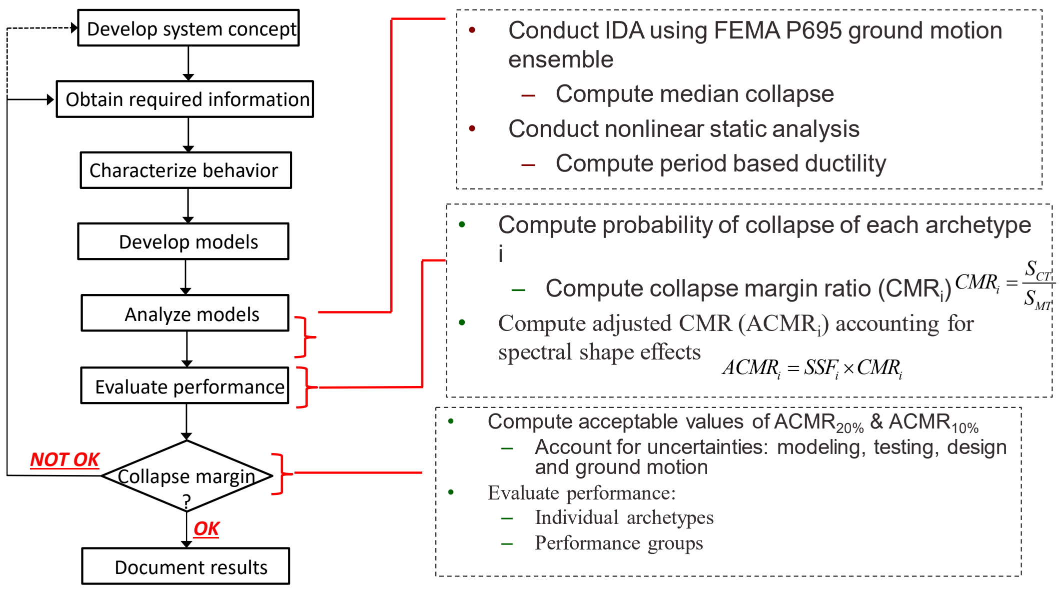

Figure 1. Overview of FEMA P695 Collapse Assessment Methodology.

In this study, several modifications to the FEMA P695 methodology were applied in order to address the questions related to the seismicity (and related ground motions) in Canada versus the US, specifically:

- Ground motions for locations such as Montreal, QC, Alma, QC, Victoria, BC and Burnaby, BC, were used as representative sites of the seismicity in Eastern and Western Canada. Montreal and Victoria were chosen as locations of large cities with highest seismicity East and West, while Alma and Burnaby were chosen as locations that have spectral acceleration S_a (0.2) close to 0.75, that differentiates moderate and high seismicity in NBCC.
- For the Victoria ground motions, the Spectral Shape Factor (SSF) was not considered since the variability of the ground motions was inherent in the three sets of the ground motions used for the analyses (crustal, sub-crustal, and subduction) [4].

The total system collapse uncertainty per the FEMA P695 methodology is a function of different sources associated with design requirements (*DR*), test data (*TD*), modeling assumptions (*MDL*) and earthquake record-to-record (*RTR*) uncertainty. Design requirements uncertainty is related to completeness and robustness of the design requirements, while record-to-record uncertainty is due to variability in response for the archetypes to different earthquake ground motions. The test data uncertainty is related to the completeness and robustness of the test data used to define/calibrate the structural system models and is (obviously) highly associated to modeling related uncertainty. Finally, modeling uncertainty is related to the correlations of the index archetypes with the structural response characteristics and associated design parameters. Modeling uncertainty is also connected to the accuracy of the numerical models to capture the collapse performance of the structural system. Respective quality ratings (β) are identified based on the different sources of uncertainty. The quality ratings are translated into quantitative values in FEMA P695 methodology based on the following scale: (i) Superior, β=0.10, (ii) Good, β=0.20, (iii) Fair, β=0.35 and (iv) Poor, β=0.50. The total collapse uncertainty was computed to be 0.65 accounting for the various uncertainties as summarized in Table 1.

$$\beta_{tot} = \sqrt{\beta_{RTR}^2 + \beta_{DR}^2 + \beta_{TD}^2 + \beta_{MDL}^2} = \sqrt{0.40^2 + 0.20^2 + 0.35^2 + 0.35^2} = 0.65 \quad (1)$$

Table 1. Summary of quality ratings used for this study.

Uncertainty	Quality Rating Value	Description
Record-to-record (β_{RTR})	0.40	Per FEMA P695 based on ground motion uncertainties
Design requirements (β_{DR})	0.20	***Good***: Completeness & robustness = High Confidence in design requirements = Medium
Test data (β_{TD})	0.35	***Fair***: Completeness & robustness = Medium Confidence in test results = Medium
Modeling (β_{MDL})	0.35	***Fair***: Representation of collapse characteristics = Medium Accuracy & robustness of models = Medium

Per the FEMA P695 methodology, acceptable structural performance is achieved if the following two criteria are met: **(i)** The average value of the adjusted collapse margin ratio of each performance group exceeds *ACMR10%,* and **(ii)** Individual values of adjusted collapse margin ratio of each individual building archetype within the performance group exceeds *ACMR20%.* The acceptable adjusted collapse margin ratio based on the total system collapse uncertainty was defined equal to 1.73 and 2.30 for 20% and 10% probability of collapse, respectively.

ARCHETYPE DEVELOPMENT & NUMERICAL MODELS

A total of 10 archetypes designed per the 2019 CSAO86 design requirements for locations of various seismicity (Victoria, Montreal, Burnaby and Alma), CLT panel aspect ratios (2:1 and 4:1), as well as number of stories (3, 6 and 10) were considered in this study representing both commercial and residential buildings. The locations of Alma, Quebec and Burnaby, BC were chosen because they had spectral accelerations S_a (0.2) of 0.785 and 0.768 respectively, that were close to the 0.75 value that separates the locations with moderate and high seismicity according to NBCC. Each archetype was a 3m long x 3m tall wall stack; essentially stacked the number of stories as designated in the archetype selection. So, for example, a 6-story archetype with a 4:1 aspect ratio would have four 0.75m long x 3m tall CLT panels making up the 3m long x 3m tall wall and stacked six times to create the 6-story archetype. A summary of the archetypes designed for this study is provided in Table 2, along with their main design characteristics designed with and R_o = 1.5 and R_d = 2.0.

Table 2. Summary of building archetypes considered in this study.

Archetype No.	Location	No. of story	Aspect Ratio	Bracket type	No. of brackets							
					Story 1	Story2	Story 3	Story 4	Story 5	Story 6	Story 7	Story 8
1	Victoria	3	2:1	BMF	8	7	4					
2	Victoria	3	4:1	90x116x48x3mm	8	7	4					
3	Montreal	6	2:1	with 18-spiral	5	5	5	4	3	2		
4	Montreal	6	4:1	nails	5	5	5	4	3	2		
5	Victoria	6	2:1		16	15	13	11	8	4		
6	Victoria	6	4:1		16	15	13	11	8	4		
7	Burnaby	10	2:1		13	13	12	12	11	10	8	7
8	Burnaby	10	4:1		13	13	12	12	11	10	8	7
9	Alma	10	2:1		8	8	7	7	6	6	5	4
10	Alma	10	4:1		8	8	7	7	6	6	5	4

A 2-dimensional model for each stacked CLT wall based on the designs presented in Table 2 was developed in RUAUMOKO2D [5]. The CLT walls were modeled with inelastic horizontal springs considering the Wayne-Steward hysteretic model. The properties of the Wayne-Steward model were obtained from previous experimental studies and data provided by FPInnovations. P-Delta (second order) effects were incorporated in the analyses.

The stacked wall model archetypes were used to conduct nonlinear time history analyses for increasing seismic intensities or incremental dynamic analyses (IDAs) using ground motion sets representative to the seismic in Canada. The median collapse of the RWFD building archetypes was defined as the median 5% damped spectral acceleration at the fundamental period of the building archetype for which 50% of the earthquake motions cause its sidesway collapse represented as numerical instabilities of the numerical model. Pushover analyses were also conducted as one of the steps required in the FEMA P695 collapse assessment methodology.

RESULTS

The focus of the present study was on determining the validity of an R_d = 2.0 for CLT structures of various aspect ratios and for various seismic demands by applying the fundamental concepts of the FEMA P695 collapse assessment methodology. The archetypes considered in this study were grouped in two performance groups based on the aspect ratio of the CLT walls designed. Considering the results of the nonlinear dynamic and static analyses to identify the adjusted collapse margin ratio for each CLT building archetype as well as the acceptable adjusted collapse margin ratio values, the archetypes were evaluated based on the FEMA P695 methodology. The collapse evaluation performance results are presented in Table 3 and Table 4 for CLT archetypes with wall aspect ratios of 2:1 and 4:1, respectively.

Table 3. Summary of building archetypes with wall aspect ratio 2:1.

Archetype ID	No. of stories	Location	ACMR	Acceptable ACMR	Pass/Fail
1	3	Victoria	2.33		Pass
3	6	Montreal	2.78		Pass
5	6	Victoria	2.37	1.73	Pass
7	10	Burnaby	2.51		Pass
9	10	Alma	2.19		Pass
	Mean of Performance Group:		**2.44**	**2.30**	**Pass**

Table 4. Summary of building archetypes with wall aspect ratio 4:1.

Archetype ID	No. of stories	Location	ACMR	Acceptable ACMR	Pass/Fail
2	3	Victoria	2.39		Pass
4	6	Montreal	2.81		Pass
6	6	Victoria	2.78	1.73	Pass
8	10	Burnaby	2.58		Pass
10	10	Alma	2.25		Pass
	Mean of Performance Group:		**2.56**	**2.30**	**Pass**

Based on the results of Tables 3 and 4, the CLT archetypes designed with the proposed R_d = 2.0 factor pass the collapse assessment criteria per the FEMA P695 methodology. Therefore, the proposed R_d = 2.0 factor is recommended for adoption in the design of CLT buildings up to 6 stories in high seismicity areas in Western Canada as well as 10 stories in moderate and low seismicity areas across the country.

CONCLUSIONS

The study presented in this paper focused on evaluating the proposed ductility-based response modification factor for CLT building construction up to 10 stories in Canada. Towards that direction, a set of 2D archetypes was designed across different locations in Canada, and consisting of different building height (i.e., the associated number of stories) and wall aspect ratios (2:1 or 4:1). Numerical models were generated based on the index archetypes to conduct static and nonlinear time history analyses as proposed by the FEMA P695 collapse assessment methodology. The results of the study revealed that the proposed R_d factor of 2.0 passes the FEMA P695 collapse assessment criteria both at the individual archetype level and the performance group level for buildings up to 6 stories located in high seismicity in Western Canada as well as for 10 story buildings located in moderate and low seismicity areas across the country.

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