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On the Methodologies for Quantification of Building Seismic Performance in Canada

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ABSTRACT

Canadian Construction Material Centre (CCMC) at National Research Council Canada (NRC) recently published a technical guide for performance evaluation of seismic force-resisting systems (SFRSs) and their force modification factors (ductility-related, R_d, and over-strength related, R_o) for use in the National Building Code of Canada (NBC). The guideline is an attempt to simplify the methodology in FEMA P-695 with efforts to reduce the computational needs by eliminating the full incremental dynamic analysis (IDA) required in FEMA P-695. This procedure requires nonlinear time history analysis (NLTHA) at 100% and 200% of code level uniform hazard spectrum (UHS), and assumes a median level of uncertainty based on a peer review panel approach. The CCMC guideline also suggests that the design seismic demand for force-controlled actions to meet the performance criteria and to take into account the uncertainty in ground motions. Meanwhile, the Seismic Resilience Team (SRT) at NRC was contracted by Codes Canada to develop a performance-based unified (PBU) procedure. While this recently developed procedure is primarily inspired by the FEMA P-695 methodology, it is yet devised with a few additional features to: 1) benefit from the concepts of performance-based design and 2) reduce the number of laborious IDA runs via a two-tiered screening procedure. The PBU procedure intends to provide a more balanced approach to evaluate SFRSs and quantify the seismic force modification factors in the NBC by using nonlinear static and time history analyses, as well as IDA as needed. The PBU procedure also considers the different sources of uncertainties in performance assessments using both screening and IDA. In this study, the PBU procedure and the CCMC's suggested nonlinear time history analysis approach are compared with the FEMA P695 procedure, via a seismic performance assessment of ductile reinforced concrete moment-resisting frame systems in the NBC.

Keywords: Seismic performance assessment, incremental dynamic analysis, seismic force-resisting systems, nonlinear time history analysis, performance-based evaluation.

INTRODUCTION

With the need for a systematic and rational methodology to evaluate the performance of the Seismic Force Resisting Systems (SFRSs) in the NBC and also to quantify their seismic force modification factors, i.e., ductility-related factor R_d and over-strength related factor R_o, two methodologies were recently developed by NRC. One of the methodologies was published by CCMC [1], referred to as CCMC methodology/procedure in this study, and it can be considered as a simplified version of the procedure in FEMA P-695 [2]. One major simplification of the FEMA P-695 procedure in the CCMC methodology is the replacement of IDA with nonlinear time history analysis using ground motions scaled at two intensity levels: 100% UHS and 200% UHS. By comparing the structural responses against the predefined performance criteria, the SFRS archetype meeting the performance criteria is considered to meet the performance target (i.e. life safety at 100% UHS, and collapse at 200% UHS). Compared with the FEMA P-695 procedure, the CCMC procedure does not require the calculation of the collapse margin ratio for performance assessment. The other methodology is the procedure developed by the SRT of NRC, referred to as the Performance-Based Unified (PBU) procedure [3]. The PBU procedure can be considered as a customized version of the FEMA P-695 procedure to suit the performance objective, seismic hazard level, and seismic design requirements in Canada. In addition, the PBU procedure incorporates several new features, such as a screening process and a performance-based assessment methodology, to enhance the assessment efficiency and extend its applicability in seismic assessments of SFRSs meeting performance levels other than collapse. This study presents a systematic evaluation of the seismic performance of ductile reinforced concrete moment-resisting frame (D-CMF) in the NBC using both the CCMC and PBU procedures and compared with FEMA P-695.

OVERVIEW OF DIFFERENT METHODOLOGIES

FEMA P-695 procedure

The evaluation procedure suggested in FEMA P-695 is shown in *Figure 1*. After obtaining the required information about the SFRS (such as results from materials, components, and system testing), archetypes that represent a typical application of the SFRS and also include irregularities permitted in the design code are developed for collapse assessment. The assessment is performed using both nonlinear pushover and dynamic time history analysis procedures. The pushover analysis is used to quantify system overstrength factor Ω and provide the period-based ductility value μ_T of each archetype, which is required in the Performance Evaluation step. After the pushover analysis, a full IDA is performed for each archetype using a set of pre-defined ground motions (44 far-field ground motion records suggested in FEMA P-695) to calculate the collapse margin ratio (CMR). As the primary parameter to characterize system safety, the CMR is defined as the ratio of the median collapse intensity ($\hat{S}_{CT}$) to the Maximum Considered Earthquake (MCE) ground motion intensity (S_{MT}). The calculated CMR needs to be adjusted for spectral shape effect by multiplying CMR with a Spectral Shape Factor (SSF) to obtain the Adjusted Collapse Margin Ratio ($ACMR$). With the 44 far-field ground motions in FEMA P-695, the SSF is simplified in the document as a function of structural period T and the period-based ductility μ_T (=$\delta_u/\delta_{y,eff}$, where δ_u and $\delta_{y,eff}$ are the ultimate displacement and effective yield displacement, respectively) and the values are provided in Table 7-1 of FEMA P-695. Then the $ACMR$s are compared against the acceptable values ($AACMR$) where various sources of uncertainty in collapse evaluation are taken into account. The total uncertainty (β_{TOT}) can be determined as:

$$\beta_{TOT} = \sqrt{\beta_{RTR}^2 + \beta_{DR}^2 + \beta_{TD}^2 + \beta_{MDL}^2} \tag{1}$$

where β_{DR}, β_{TD}, and β_{MDL} are assumed to be 0.1 (Superior), 0.2 (Good) and 0.2 (Good) in this study to present uncertainties related to design requirements, test data, and modelling, respectively; For the 44 far-field ground motions in FEMA P-695, the following simplified equation is used to determine β_{RTR}:

$$\beta_{RTR} = 0.1 + 0.1\mu_T \leq 0.4 \tag{2}$$

The SFRS is considered to have an acceptable safety margin against collapse if the $ACMR$ is no less than the acceptable $ACMR$.

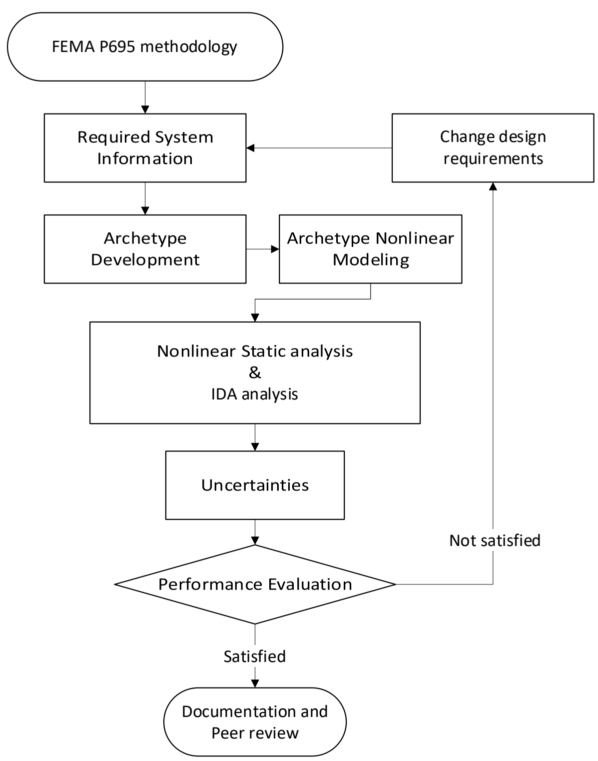

Figure 1. Flowchart of FEMA P-695 methodology [2]

CCMC procedure

The CCMC procedure simplifies the FEMA P-695 procedure by replacing the laborious IDA for each archetype with time history analyses using a set of selected ground motions scaled at 100% and 200% UHS intensities. For the ground motions scaled at 100% UHS intensity, if more than 10% of the total ground motions result in unacceptable structural responses, the archetype design is considered unacceptable. Furthermore, another set of time history analyses is performed with the selected ground motions scaled at 200% of the UHS intensity. More details about the CCMC procedure are shown in *Figure 2*. Examples of unacceptable responses are dynamic instability, non-convergent analysis, and force or deformation demand on an element that exceeds the force or deformation capacity of that element. For all responses of motions that are scaled to 100% of UHS, the inter-storey drift limits per the NBC shall also be respected, i.e., 2.5% for normal importance building category. For responses of ground motions that are scaled to 200% of UHS, the absolute value of the maximum inter-storey drift from the suite of analyses shall not exceed 4.5%. Assuming a median level of total uncertainty, the SFRS is considered to have an adequate CMR if less than 50% of the ground motions lead to an unacceptable response for each developed archetype.

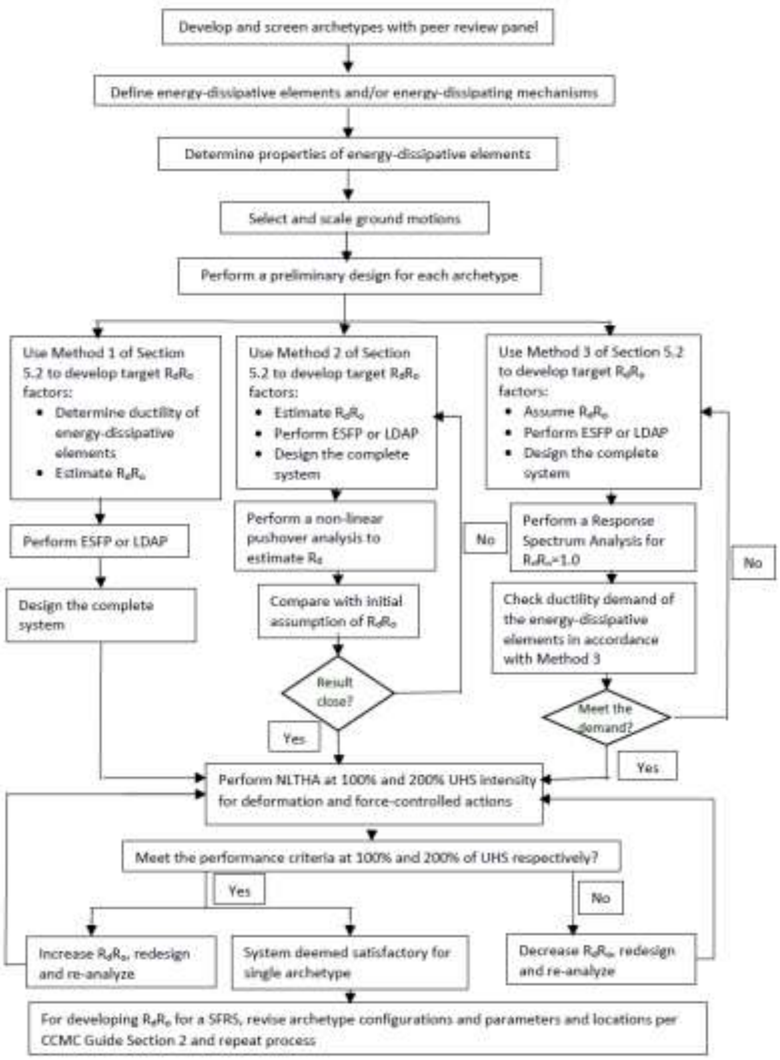

Figure 2. Flowchart of CCMC methodology [1]

As suggested in the CCMC procedure, the set of ground motions for the analyses should be selected according to the requirements in the appendix to NBC Commentary J [4]. In this comparative study, 44 ground motions selected for Vancouver are used for the performance assessment of D-CMF using the CCMC procedure.

PBU procedure

The PBU procedure is primarily inspired by the FEMA P-695 in terms of the collection of system information, archetype development, and archetype nonlinear modelling. Major changes are made to the analysis and the performance evaluation steps as shown in *Figure 3*. Specifically, there is a two-tier screening process prior to the IDA with the purpose of reducing the required number of archetypes for going through the IDA. The screening process starts with a nonlinear pushover analysis of each archetype, also referred to as preliminary screening, to obtain the overstrength-related factor R_o and period-based ductility factor μ_T. The archetypes with the calculated R_o less than the specified values for design are sent back to Step 1 by changing the design requirements. Otherwise, nonlinear time history analysis is performed for each archetype with a set of ground motions to be scaled as follows:

- The ground motions are first scaled to the code-level earthquake spectrum at the structural fundamental period. Then they are scaled up again using a scale factor of $APMR_{10\%}$ (i.e., 2.16) which represents the acceptable adjusted performance margin ratio ($APMR$) for a probability of exceedance of 10% and a total of uncertainty (β_{TOT}) of 0.6 against the target performance level, such as Immediate Occupancy (IO), Life Safety (LS), or Collapse Prevention (CP). If no less than half of the selected ground motions result in acceptable responses, the archetype is considered as passed. If all archetypes in the performance group (PG) pass the screening, the PG is identified as non-critical and all archetypes of the PG are exempted from the IDA.
- Otherwise, all archetypes need to be further screened with the ground motions scaled by a higher factor of $APMR_{6\%}$ (i.e., 2.54) which represents the $APMR$ for a probability of exceedance of 6% and β_{TOT} of 0.6. This time, if the half the number of archetypes within a PG is passed, the PG is non-critical and only the failed archetypes require IDA. Otherwise, IDA should be performed for all archetypes within the PG.

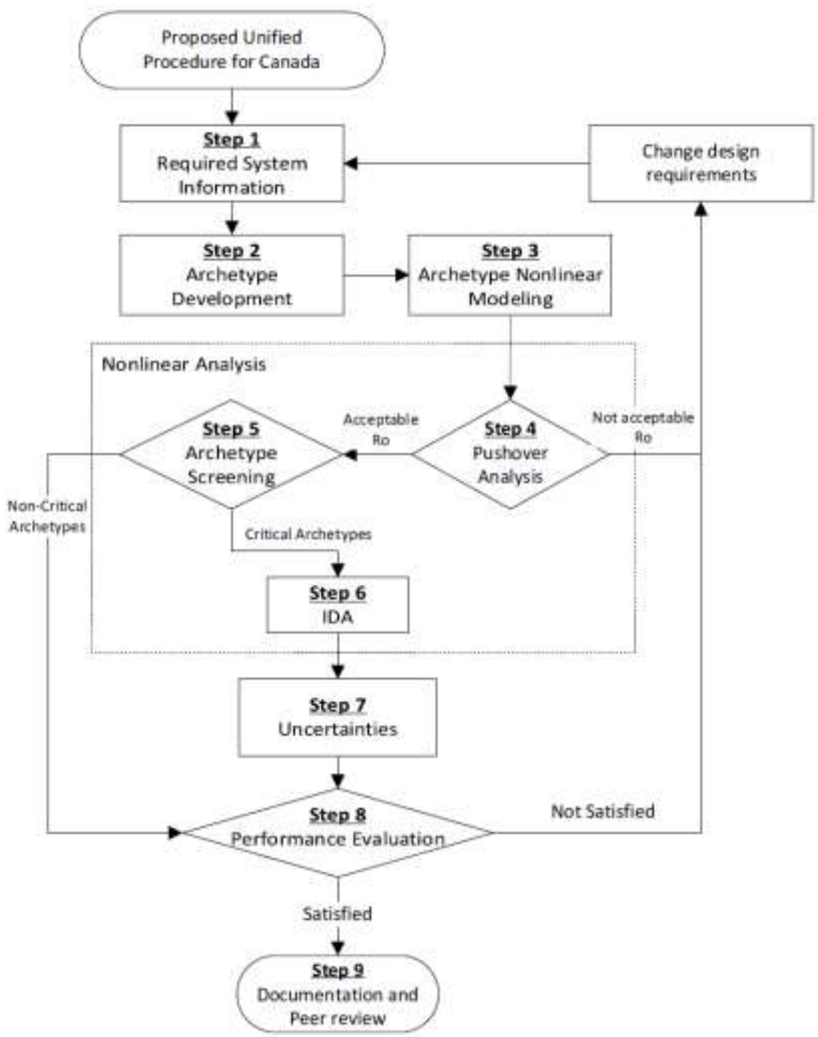

Figure 3. Flowchart of PBU methodology [3]

As suggested in the PBU procedure [5], both the screening and IDA processes are based on the same acceptance criteria. Specifically, the performance levels of a system are defined globally by drift limits and locally by component-based acceptance criteria. Additionally, in cases where the valid range of modelling and non-convergence criteria govern the seismic response in lower intensities, they are recommended to be considered as the control points of a system. For example, inter-storey drift ratios of 1.0%, 2.5%, and 4.5% can be used as the global criteria for IO, LS, and CP performance levels, respectively. For the local criteria, the plastic hinge rotation limits of beams, columns, and joints, as suggested in ASCE 41-17 [6] based on various experimental studies, could be used. In this study, however, only the local criteria based on ASCE 41-17 are considered to evaluate the performance of D-CMF following the FEMA P-695 and PBU procedures. This is because the inclusion of global drift limits, such as 2.5% for LS, in the performance evaluation process is considered to be too conservative for D-CMF according to the study by Dolati and Saatcioglu (2022) [7].

After the screening and IDA processes, the performance margin ratio (PMR) is determined and then adjusted for spectral shape effect to obtain the Adjusted PMR ($APMR$). By comparing with the acceptable $APMR$ values, the performance of the SFRS can be quantified. Note that in the FEMA P-695 procedure, only the margin ratio against collapse is determined (i.e., collapse margin ratio).

Unlike to the FEMA P-695 where a fixed ground motion set is provided for all archetypes, the PBU procedure provides two methods for the selection of ground motions required for both screening and IDA. Specifically, the ground motion set can be selected based on earthquake magnitudes, source-to-site distances, and with or without considering the spectral shape effect. In this study, the method without considering the spectral shape effect in the selection of ground motions is adopted. The same 44 ground motions for Vancouver are used for performance assessment using the PBU procedure in this study. The influence of the spectral shape effect on $APMR$ is taken into account by applying a spectral shape factor. Due to the use of a set of ground motions different from the fixed ground motion set suggested in FEMA P-695, the *SSF* needs to be calculated instead as follows:

$$SSF = \exp(\beta_1 \, [\bar{\varepsilon}_0 \, (T) - \bar{\varepsilon}_{record} \, (T)]) \tag{3}$$

where $\bar{\varepsilon}_0 \, (T)$ and $\bar{\varepsilon}_{record} \, (T)$ are mean epsilon values at the structural period T of the site from deaggregation analysis and the general set of selected records, respectively; The factor β_1 represents the sensitivity of median performance spectral intensity at T to the ε value of each motion record, $\varepsilon_{record}(T)$. In addition, the use of the ground motion set for Vancouver results in β_{RTR} different from the values calculated by Eq. (2) for the fixed far-field ground motions in FEMA P-695. Specifically, β_{RTR} in the PBU procedure can be calculated directly from the IDA of each archetype.

The differences between the FEMA P-695, CCMC, and PBU procedures are summarized in *Table 1*.

Table 1. Comparison of different methodologies

	FEMA P-695	CCMC	PBU
Preliminary screening	No	Yes (Qualitative Assessment)	Yes (Pushover Analysis)
Detailed screening	No	No	Yes (NLTHA)
Overstrength factor	Ω based on maximum values	R_o based on the concepts in Mitchell et al. (2003) [8] and peer review panel discussion	R_o based on minimum values from pushover analyses
IDA requirement	Required for all archetypes	No	Required for archetypes not passing the screening
Ground motions	Fixed set (far-field)	Selection of ground motions suitable for the building site according to the requirements in NBC commentary J	Two different approaches for ground motion selection
Total uncertainty	Calculated	$\beta_{TOT} = 0.5$	Calculated: different for different ground motion selection methods
Spectral shape factor	Yes	No	Only needed for one of the ground motions selection approaches
Acceptance criteria	Collapse	Life safety objective at 100% UHS and collapse at 200% UHS	Collapse Prevention, Life Safety, Immediate Occupancy

Performance evaluation	Risk-based using different acceptable ACMR against collapse for different risk categories as suggested by NIST GCR12-917-20 [9] for each archetype and each performance group for each archetype and performance groups	Risk-based based on design checks for 100% UHS and 200% UHS intensities for each archetype, and design of force-controlled actions need to meet the required seismic demand.	Performance-based using constant acceptable APMR against different performance levels not met for different importance categories for each archetype and each performance group

SFRS EXAMPLE

The SFRS example considered in this study for comparison of different methodologies is the ductile reinforced concrete moment-resisting frame. As shown in *Table 2*, six Performance Groups (PGs) were developed with fifteen (15) archetypes considering various key configuration parameters, such as gravity load level, seismic category, geometric variation, and system irregularity. The design of the archetypes followed the requirements in the NBC 2015 and CSA A23.3-14. An ID number is given to each archetype, where the letter D represents the D-CMF; the numbers after the dash indicate the number of building storeys; "S4" represent the High seismic categories; "H" and "L" represent high and low gravity load levels, respectively; "B5" and "B8" represent frames with equal span lengths of 5 m and 8 m, respectively; and different irregularity types are given with "S", "W", and "V" for the soft storey, weak storey and vertical irregularities, respectively. More details about the archetype development, design and modelling can be found in the [5].

Table 2. D-CMF archetypes

PG #	Bay Length (m)	Gravity Load Level	Seismic Category	Irregularity Type	Period Domain	T (sec)	Storeys	Archetype ID
1	5.7-8	High	SC4	Regular	Long	0.54	2	D-2S4H
						1.14	6	D-6S4H
						1.89	12	D-12S4H
						2.75	20	D-20S4H
2	5.7-8	Low	SC4	Regular	Long	0.54	2	D-2S4L
						1.14	6	D-6S4L
						1.89	12	D-12S4L
3	5.5	High	SC4	Regular	Long	1.89	12	D-12S4HB5
4	8	High	SC4	Regular	Long	1.89	12	D-12S4HB8
5	5.7-8	High	SC4	Soft Storey	Long	0.61	2	D-2S4HS
						1.18	6	D-6S4HS
						1.94	12	D-12S4HS
6	5.7-8	High	SC4	Vertical	Long	0.54	2	D-2S4HV
						1.14	6	D-6S4HV
						1.89	12	D-12S4HV

PERFORMANCE ASSESSMENT RESULTS

Due to the use of different performance criteria and set of ground motions as suggested in different procedures, it is not easy to make a fair comparison between the three methods. However, with the same purpose of understanding the safety margin against collapse, the CCMC procedure is compared with FEMA P-695 in this study. On the other hand, the PBU procedure is compared with the FEMA P-695 to discuss their differences in the calculated collapse margin ratio against collapse and also demonstrate the benefits of the PBU procedure for performance-based assessment.

Table 3 presents the calculated $ACMR$ and $APMR$ values using the PBU procedure with respect to CP and compared with the FEMA P-695 procedure. The acceptance criteria for the performance assessment are based on ASCE 41-17. It can be noted that the $ACMRs$ and $APMRs$ are all greater than the corresponding acceptable values, which indicates that the D-CMF system has sufficient safety margin against collapse based on the design requirements in the NBC 2015 and CSA A23.3-14. The average ratio between $ACMR$ and $AACMR$ of all PGs based on the FEMA P-695 procedure is 1.38 compared with 1.35, the average ratio $APMR$ to $AAPMR$ based on the PBU procedure. For all archetypes except D-20S4H, the calculated APMR values in the PBU procedure are less than the corresponding ACMR values. Such an inconsistent tend in the archetype D-20S4H is mainly due to the use of different ground motion sets for the two performance assessment methodologies (i.e., FEMA-P695 and PBU). For more information about the influence of the ground motion set on the calculated performance margin ratio can be found from a previous study by Huang et al. [10]. Different from the FEMA P-695 procedure which only focuses on collapse performance, the PBU procedure also allows for evaluating performance margins against other performance objectives (i.e., IO and LS). As shown in *Table 3*, given that the calculated APMRs of several archetypes are less than the AAPMRs for IO and LS levels, the considered D-CMF can only achieve CP.

The performance assessment results based on the CCMC methodology and the FEMA P-695 are compared and presented in *Table 4*. It is important to note that drift limit requirements are included in the performance criteria using the CCMC methodology, however they are not included in the performance criteria using the FEMA P-695 methodology. For the 100% UHS check, all archetypes are not meeting the requirements with the number of failed ground motions greater than 10% of the total number of ground motions, i.e., four ground motions. It can be noted that, for each archetype, there are more than 10 ground motions that result in the maximum inter-storey drift greater than 2.5%. It should be noted that all archetypes were designed to meet the 2.5% inter-storey drift requirements of the NBC using the response spectrum method. The unacceptable performance criteria, defined using the inter-storey drift limit of 2.5% in the NBC for life safety, is found to be more stringent than the local criteria for LS based on the plastic hinge limits in ASCE 41-17. For reference, the number of failed GMs after excluding the drift limit of 2.5% is also included in *Table 4* and it can be noted that only three archetypes, i.e., D-2S4L, D-6S4L, and D-6S4HS, failed to pass the 100% UHS check. It can be seen from the results that the drift limit is the governing failure mode for majority of the archetypes when it is considered as one of the performance criteria. Therefore, the study indicates that the inter-storey drift limit of 2.5% is quite conservative for describing the structural behaviour of D-CMF without consideration for non-structural components design requirements in NBC. For the 200% UHS check, since only two out of 15 archetypes exhibit acceptable responses, the D-CMF is considered to have an insufficient safety margin against collapse at 200% UHS based on the CCMC methodology. On the other hand, the conclusions based on more detailed performance assessments using the FEMA P-695 and PBU methodologies suggest that D-CMF meet the collapse prevention performance level. Compared with the FEMA P-695 and PBU procedures, the CCMC procedure is thus considered to be more conservative. It is understandable because the CCMC procedure is equivalent to requiring a minimum collapse margin ratio of 2.0 for assumed median level of uncertainty and without consideration for further increasing the CMR with spectral shape factor (SSF). However, the spectral shape factor is used in both FEMA P-695 and PBU methodologies. It is also worth noting that in another study shows that the simplified performance-based design procedure outlined in the CCMC/NRC technical guide can be used as an efficient tool to design a robust seismic force-resisting systems [11].

Table 3. Performance evaluation table using FEMA P-695 and PBU methodologies

PG	Archetype	FEMA P-695			PBU				
		ACMR	AACMR	Status	APMR			AAPMR*	Status (CP)
					IO	LS	CP		
1	D-2S4H	3.16	1.52	OK	0.57	1.74	2.21	1.52	OK
	D-6S4H	3.43	1.52	OK	0.53	1.48	2.15	1.58	OK
	D-12S4H	3.24	1.52	OK	0.82	2.03	2.99	1.55	OK
	D-20S4H	2.70	1.52	OK	0.85	1.84	3.40	1.75	OK
	PG	3.13	1.9	OK	OK	1.77	2.69	2.05	OK
2	D-2S4L	3.82	1.52	OK	0.58	1.30	1.88	1.56	OK
	D-6S4L	3.39	1.52	OK	0.51	1.28	2.01	1.56	OK
	D-12S4L	2.69	1.52	OK	0.75	1.58	2.55	1.47	OK
	PG	3.30	1.9	OK	OK	1.39	2.14	1.92	OK
3	D-12S4HB5	3.24	1.52	OK	0.76	1.85	2.81	1.51	OK
4	D-12S4HB8	3.36	1.52	OK	0.79	1.81	3.38	1.51	OK
5	D-2S4HS	2.99	1.52	OK	0.60	1.61	2.31	1.58	OK
	D-6S4HS	3.00	1.52	OK	0.50	1.28	2.25	1.61	OK
	D-12S4HS	2.95	1.52	OK	0.61	1.70	2.83	1.56	OK
	PG	2.98	1.9	OK	OK	1.53	2.46	2.02	OK
6	D-2S4HV	2.27	1.52	OK	0.58	1.45	1.65	1.57	OK
	D-6S4HV	3.51	1.52	OK	0.71	1.56	2.14	1.47	OK
	D-12S4HV	3.70	1.52	OK	0.78	1.60	2.63	1.43	OK
	PG	3.16	1.9	OK	OK	1.54	2.14	1.84	OK

*The values are calculated for CP performance level.

Table 4. Performance evaluation results based on CCMC methodology

Archetype	100% UHS				200% UHS				P695		
	NF		ANF	Status	NF		ANF	Status	ACMR	Adjusted ACMR	Status
	2.5% excluded	2.5% included			4.5% excluded	4.5% included					
D-2S4H	2	19	4	NG	23	35	22	NG	3.15	1.52	OK
D-6S4H	3	19	4	NG	24	26	22	NG	2.86	1.52	OK
D-12S4H	1	12	4	NG	13	21	22	OK	2.51	1.52	OK
D-20S4H	3	16	4	NG	18	25	22	NG	2.33	1.52	OK
D-2S4L	5	20	4	NG	24	32	22	NG	2.83	1.52	OK
D-6S4L	6	23	4	NG	26	33	22	NG	2.46	1.52	OK
D-12S4L	0	11	4	NG	29	43	22	NG	2.13	1.52	OK
D-12S4HB5	0	14	4	NG	18	24	22	NG	2.50	1.52	OK
D-12S4HB8	0	10	4	NG	12	18	22	OK	2.74	1.52	OK
D-2S4HS	2	27	4	NG	15	34	22	NG	2.79	1.52	OK
D-6S4HS	6	32	4	NG	23	38	22	NG	2.80	1.52	OK
D-12S4HS	2	20	4	NG	19	27	22	NG	2.40	1.52	OK
D-2S4HV	0	18	4	NG	21	29	22	NG	2.27	1.52	OK
D-6S4HV	2	22	4	NG	19	36	22	NG	2.82	1.52	OK
D-12S4HV	0	20	4	NG	16	30	22	NG	2.82	1.52	OK

Note: NF: number of failed GMs; ANF: acceptable number of failed GMs

CONCLUSIONS

This study compares the CCMC and PBU procedures with the FEMA P-695 methodology for evaluating the seismic performance of a selected SFRS in the NBC (i.e., ductile reinforced concrete moment-resisting frame system). It is found that the use of PBU procedure results in similar performance margins against collapse as that in FEMA P-695 and the D-CMF in the NBC 2015 can achieve CP with a sufficient safety margin. Such a conclusion is derived with less computational effort via the two-tiered screening procedure of the PBU procedure. The PBU procedure is also devised to include the seismic assessment of the SFRSs for performance levels other than CP (i.e., LS or IO). Using the PBU procedure, the performance margin ratios for IO and LS are also calculated and compared against the acceptable values. It is found that the D-CMF in the NBC 2015 does not have an acceptable margin against IO or LS if designed without the increase in seismic forces by the importance factor (I_E) as prescribed in NBC.

It is, nevertheless, difficult to compare the CCMC procedure with FEMA P-695 procedure used in this study, due to the different performance criteria used. Only the global collapse criteria are considered to evaluate the performance of D-CMF following the FEMA P-695 procedure; while global criteria with drift limit requirements in addition to local criteria are considered to evaluate the performance of D-CMF following the CCMC procedure. It can be seen from the results that the drift limit is the governing failure mode for the majority of the archetypes at 100% UHS when it is considered as one of the performance criteria. At the median level of total uncertainty, the CCMC procedure is more conservative than the FEMA P-695 procedure, by requiring a minimum collapse margin ratio of 2.0 for an assumed median level of uncertainty without consideration for the spectral shape factor (SSF) which further increases in the CMR. Both FEMA P-695 and PBU procedures, however, include the effect of spectral shape factor, which subsequently increases the CMR and PMR values for each archetype, as well as accounting for various sources of uncertainties via a more systematic/detailed procedure.

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REFERENCES

[1] R. DeVall, M. Popovski, J. McFadden, "Technical guide for evaluation of seismic force resisting systems and their force modification factors for use in the National Building Code of Canada with concepts illustrated using a cantilevered wood CLT shear wall example," National Research Council Canada, Ottawa, Canada, 2021.

[2] FEMA, Quantification of building seismic performance factors, Washington, D.C.: Applied Technology Council for the Federal Emergency Management Agency, 2009.

[3] F. Fazileh, R. Fathi-Fazl, A. Dolati, C. Ventura, M. Saatcioglu, D. Lau, T. Yang, V. Sadeghian and J. Erochko, "Methodology for determination of seismic force modification factors in Canada: Performance-based unified procedure," Earthquake Spectra, 2023.

[4] Canadian Commission on Building and Fire Codes. Standing Committee on Structural Design, "Structural commentaries (user's guide: NBC 2015: Part 4 of Division B)," National Research Council Canada, Ottawa, Canada, 2015.

[5] F. Fazileh, R. Fathi-Fazl and X. Huang, Final Report #A1-018030 "Performance-based unified procedure for determination of seismic force modification factors R_d, R_o in NBC," National Research Council of Canada, Ottawa, 2023.

[6] ASCE 41-17, "Seismic evaluation and retrofit of existing buildings," American Society of Civil Engineering, Reston, Virginia, 2017.

[7] A. Dolati, M. Saatcioglu, "Assessment of Seismic Force Modification Factors for Concrete Moment Frame Structures in Canada Using Draft Performance-Based Unified Procedure", March 2022.

[8] D. Mitchell, R. Tremblay, E. Karacabeyli, P. Paultre, M. Saatcioglu and D. L Anderson, "Seismic force modification factors for the proposed 2005 edition of the National Building Code of Canada," Canadian Journal of Civil Engineering, vol. 30, pp. 308-327, 2003.

[9] National Institute of Standard and Technology (NIST), "Tentative framework for development of advanced seismic design criteria for new buildings," National Institute of Standards and Technology, Gaithersburg, Maryland, 2012.

[10] X. Huang, F. Fazileh, A. Behamzadeh, R. Fathi-Fazl, “Effect of ground motion set on performance assessment of structures using performance-based unified procedure,” CSCE Annual Conference, Moncton, NB, 2023.

[11] T. Y. Yang, S. Lepine-Lacroix, J. A. Ramos Guerrero, J. B. W. McFadden and M. A. Q. Al-Janabi, "Seismic performance evaluation of innovative ballon type CLT rocking shear walls," Resilient Cities and Structures, vol. 1, no. 1, pp. 44-52, 2022.