Leadership in Sustainable Infrastructure

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Vancouver, Canada

May 31 – June 3, 2017/ *Mai 31 – Juin 3, 2017*

SEISMIC DISPLACEMENT DEMAND ESTIMATION FOR FRAGILITY ASSESSMENT OF REINFORCED CONCRETE FRAME BUILDINGS

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Abstract: Seismic risk assessment at regional scales involves seismic hazard, inventory of assets at risk and respective vulnerability. Vulnerability refers to the susceptibility to earthquake impacts defined by the potential physical damages and resulting economic and social losses. Central to the vulnerability modelling is the concept of fragility function that correlates the expected structural damage to increasing levels of seismic intensity. Fragility functions combine a probabilistic seismic demand model and a probabilistic damage model. The probabilistic seismic demand model correlates a seismic intensity measure (IM) such as the spectral acceleration at the fundamental period of the building, $Sa(T_1)$, to an engineering demand parameter (EDP) that better correlates with damage such as the maximum inter-story drift. The probabilistic damage model correlates the EDP to threshold damage states (e.g. slight, moderate, extensive, and complete). This paper presents the development of a new simplified probabilistic seismic demand model applicable for fragility analysis of ductile medium and high rise reinforced concrete moment resisting frame buildings (RC-MRF) for regional seismic risk studies. The model provides a direct correlation between the maximum inter-story drift to the $Sa(T_1)$ using a new period dependent displacement coefficient. A database was compiled from literature sources of maximum inter-story drift seismic demand predictions using nonlinear finite element models for ductile RC-MRF that were subjected to increasing levels of ground motion intensities. The model was applied to develop fragility functions for a case study ductile 16-story high-rise RC-MRF building that conforms to the provisions of the 2005 National Building Code of Canada and estimate probable damage for 2% and 10% probability of exceedance in 50 years.

1 INTRODUCTION

The seismic risk assessment at a regional scale is central to planning mitigation, preparedness and emergency response measures in earthquake-prone regions. Seismic risk assessment at regional scales involves the development of seismic hazard models, compilation of inventory databases of assets at risk (e.g. buildings and infrastructure) and the development of respective vulnerability models. Vulnerability refers to the susceptibility to earthquake impacts defined by the potential physical damage and resulting economic and social losses. Central to the vulnerability modelling is the concept of fragility function that correlates the expected structural damage to increasing levels of seismic intensity (Abo-El-Ezz et al. 2014). For vulnerability assessment of a specific building, fragility functions are typically developed by combining a probabilistic seismic demand model and a probabilistic damage model. The probabilistic seismic demand model is defined as a closed-form relationship between a seismic intensity measure (IM) and the median and standard deviation of an engineering demand parameter (EDP) that better correlate to damage. This requires generating a computer model of the structural system of the building and subjecting this model to a suite of ground motion records scaled at increasing levels of a seismic intensity measure (IM) such as the spectral acceleration at the fundamental period of the building, $Sa(T_1)$

(Ellingwood et al. 2007). This is typically called the incremental dynamic analysis. Results of incremental dynamic analysis for several ground motion records can be expressed in the form of IM versus an engineering demand parameter (EDP). The probabilistic seismic demand model correlates the median IM to the EDP and provides an estimate of the variability in seismic demand in terms of a standard deviation. The median IM to the EDP relationship and the corresponding standard deviation are estimated using regression analysis of the incremental dynamic analysis results. In view of developing a fragility model, maximum inter-story drift (ISD) is generally chosen as EDF as it correlates well with damage. The probabilistic damage model correlates the EDP (in this case, the ISD) to threshold damage states (e.g. slight, moderate, extensive, and complete) based on experimental observations of damage progression. The development of the seismic demand model based on incremental dynamic analysis involves the selection and scaling of a suite of ground motion records, the preparation of a nonlinear structural model of the buildings with suitable force-deformation relationships of the structural components and the processing and interpretation of large data. It therefore represents the most time-consuming component of the fragility functions development process and is a suitable approach for fragility analysis of specific individual buildings. On the other hand, for regional scale seismic risk assessment studies, simplified probabilistic methods are needed for rapid evaluation of seismic fragility of a portfolio of buildings. Fragility functions can be developed using observed damage from past earthquakes or analytical modelling of prototype buildings if post-earthquake damage observations are scarce. These prototypes represent a portfolio of buildings with common material, lateral load resisting system, height and seismic design code level. For example, Hazus (FEMA, 2013) tool for regional-scale risk assessment classify ductile reinforced concrete moment resisting frame buildings (RC-MRF) according to height range; low rise with less than 3 stories; mid-rise with 4 to 7 stories and high rise with more than 7 stories. However, this classification does not consider the variability in the fundamental period of buildings which have a direct effect on the expected seismic displacement demands.

The objective of this paper is to present the development and application of a new simplified probabilistic seismic demand model for rapid fragility analysis of ductile medium and high rise reinforced concrete moment resisting frame buildings (RC-MRF). The proposed model applies a new period dependent displacement coefficient relationship that directly correlate the median maximum ISD to the Sa(T_1) and provide an estimate of the corresponding standard deviation. The period dependent displacement coefficient relationship is proposed based on statistical analysis of a database of maximum ISD seismic demand predictions using nonlinear finite element models for ductile RC-MRF that were subjected to increasing levels of ground motion intensities. The database was compiled from literature resources. An example application of the fragility model is presented to demonstrate the development of fragility functions of a case study 16-story high-rise RC-MRF building that conforms to the provisions of the 2005 National Building Code of Canada (NRCC, 2005). These fragility functions are then used to estimate probable damage distribution for seismic hazard with 2% and 10% probability of exceedance.

2 PROBABILISTIC SEISMIC DEMAND MODEL

Standard simplified seismic displacement demand prediction methods include the capacity spectrum method and the displacement coefficient method. These methods require a capacity curve of the building model that is typically conducted using nonlinear pushover analysis. This analysis would require detailed modelling of the nonlinear force-deformation relationships and details of the geometrical and material characteristics of the buildings. On the other hand, a rapid simplified method for displacement demand prediction would be more suitable for the assessment of a portfolio of buildings without the need for detailed drawings and analysis of each specific building.

In the framework of simplified estimates of seismic displacement demand of frame buildings, displacement coefficient procedures that do not require pushover analyses were proposed (Gupta and Krawinkler 2000; Medina and Krawinkler 2005). These procedures are based on modifying the spectral displacement demand at the fundamental period of the building with a coefficient that relates the roof drift to the spectral displacement and a coefficient that relates the inter-story drift to the roof drift. These procedures were mainly developed to estimate the median drift demand for preliminary design or assessment of frame buildings with little consideration of how to quantify the variability in seismic demand which is critical for fragility analysis. On the other hand, this paper presents the development of a single period-dependent displacement coefficient that provides a direct correlation between the median ISD and the IM. This coefficient takes into account the multi-degree of freedom effects on the drift demand in frame buildings. This direct correlation is more suited for rapid fragility analysis of a portfolio of buildings. The period dependent displacement coefficient is calibrated based on a database of maximum inter-story drift seismic demand predictions using nonlinear finite element models for ductile RC-MRF that were subjected to increasing levels of ground motion intensities (Table 1).

The database consists of 15 reinforced concrete frame building models that were designed according to the seismic provisions of various worldwide national modern building codes. Four frames were designed according to the seismic provisions of the European standards (Eurocode-8. 2003; Jankovic and Stojadinovic 2004); three frames were designed according to the seismic provisions of the 2005 National Building Code of Canada (NRCC 2005; Lin 2008); three frames were designed according to the seismic provisions of the 1985 NBCC (NRCC 1985; Tesfamariam et al. 2013); two frames were designed according to the seismic provisions of the 2002 American Society of Civil Engineering (ASCE7-02. 2002; Rajeev et al. 2014) and three frames were designed according to the 2010 seismic provisions of Chinese Code for Seismic Design of Buildings (NSPRC 2010; Wu et al. 2012). Despite that fact that these case studies represent buildings designed according to different codes, they were designed according to the well-known capacity design principle integrated in modern building codes. This principle assures a ductile failure mechanism and energy dissipation capacity through beam-hinging mechanism. The difference in the lateral stiffness between these buildings is approximately captured through the variation in the fundamental period (T_1) based on eigenvalue analysis of cracked stiffness for beam-column elements. The frame model varies in height from 3 to 16 stories with fundamental period (T_1) ranging from 0.56 to 2.75 sec. Nonlinear frame element modelling approach was used to simulate the seismic response of the frames. Based on analysis of the maximum ISD demands corresponding to increasing levels of seismic intensity in terms of $Sa(T_1)$, new closed-form equations are developed to predict the median ISD corresponding to $Sa(T_1)$ (Equations 1, 2 and 3).

[1] $ISD = C.\left[\frac{Sd(T_1)}{H}\right]$

[2] $Sd(T_1) = \left[\frac{T_1^2}{4\pi^2}\right] Sa(T_1).g$

[3] $C = 0.5T_1 + 1.2$

C is the period dependent coefficient that was calibrated based on the results of nonlinear incremental dynamic analyses from the database frames; T_1 is the fundamental period of the frame; H is the frame height in metres and g is the gravitational acceleration (9.81 m/sec^2). Figure 1 shows the calibration of the period dependent coefficient (C). Each point represents the average of the ratio of the median ISD from time history analysis (THA) to $[Sd(T_1)/H]$ for a given frame. An example calculation of the average C coefficient for a given frame is shown in Table 2.

The above equations can be used to predict the median drift demands. For fragility analysis, it is important to quantify the uncertainty in the seismic drift demand originating from the record-to-record variability in ground motion input. The uncertainty in seismic drift demand is typically represented by a log normal standard deviation (β_D). In order to provide a simplified approach for fragility analysis of RC-MRF, an estimate of the log normal standard deviation of the seismic drift demand is required. Based on analysis of the reported log normal standard deviations (β_D) from time history analysis in the database, the β_D values varied from 0.15 to 0.45 with no apparent correlation with the fundamental period (Figure 2). An average value of ($\beta_D = 0.3$) is proposed for simplified fragility analysis.

Table 1: Database of frames used to estimate the seismic drift demand model

Frame-ID	Number of stories (N)	Fundamental period (T_1), [sec]	Frame height (H), [m]	Seismic design code	Reference
F1	4	1.02	12.8	Eurocode-8	Jankovic and Stojadinovic (2004)
F2	6	1.2	19.2	Eurocode-8	Jankovic and Stojadinovic (2004)
F3	8	1.7	25.6	Eurocode-8	Jankovic and Stojadinovic (2004)
F4	12	2.57	38.4	Eurocode-8	Jankovic and Stojadinovic (2004)
F5	4	0.94	14.6	NBCC-2005	Lin (2008)
F6	10	1.96	36.5	NBCC-2005	Lin (2008)
F7	16	2.75	58.4	NBCC-2005	Lin (2008)
F8	3	0.56	10.9	NBCC-1985	Tesfamariam et al. (2013)
F9	6	1.11	21.9	NBCC-1985	Tesfamariam et al. (2013)
F10	9	1.77	32.8	NBCC-1985	Tesfamariam et al. (2013)
F11	4	1	15.6	ASCE7-02	Rajeev et al. (2014)
F12	8	1.8	31.2	ASCE7-02	Rajeev et al. (2014)
F13	3	0.53	9.9	CCSDB-2010	Wu et al. (2012)
F14	6	1.1	19.8	CCSDB-2010	Wu et al. (2012)
F15	9	1.43	29.7	CCSDB-2010	Wu et al. (2012)

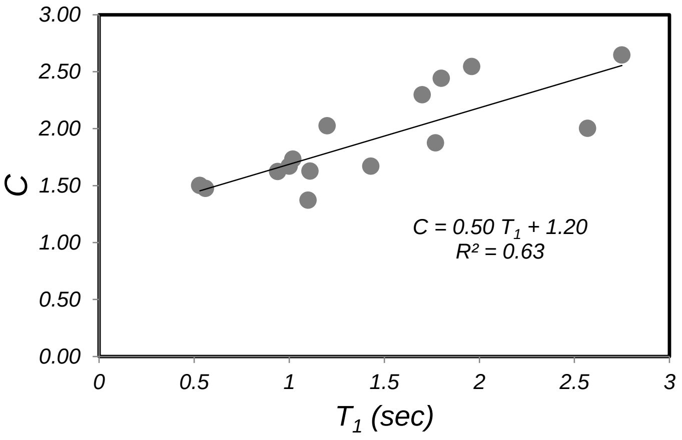

Figure 1: The calibration of the period dependent coefficient (C).

Table 2: Example calculation of the average C coefficient for a 4-story frame (T_1=1.02) (F1 Frame)

Median ISD [%] (THA)	$Sa(T_1)$	$Sd(T_1)$ [m]	[100*$Sd(T_1)$/H]	C = Median ISD% / [$Sd(T_1)$/H]
0.46	0.15	0.04	0.30	1.52
0.63	0.20	0.05	0.40	1.57
2.55	0.70	0.18	1.41	1.80
3.78	1.00	0.26	2.02	1.87
4.21	1.10	0.28	2.22	1.89
			Average C	1.73

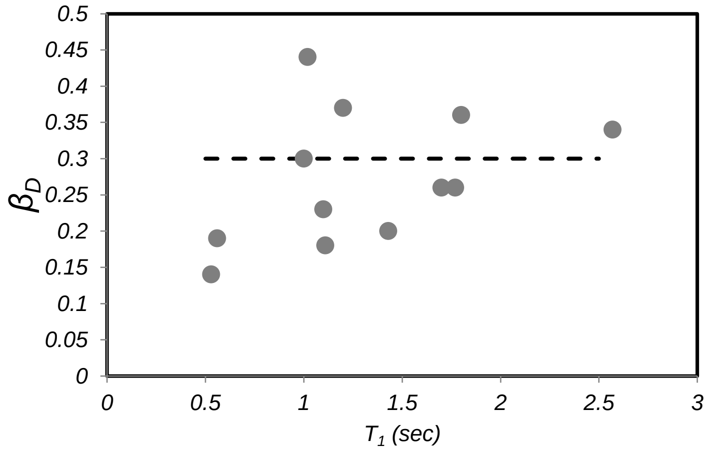

Figure 2: Reported log normal standard deviation (β_D) of the seismic drift demand in the database.

3 SIMPLIFIED FRAGILITY ANALYSIS

This section presents the implementation of the simplified probabilistic seismic demand model for the development of fragility functions of reinforced concrete frame buildings. Analytical fragility functions are usually given in the form of log normal distribution of the probability of being in or exceeding a given damage state for a given IM (e.g. $Sa(T_1)$). The conditional probability of reaching a specific damage state (DS), given the IM, is defined by Equations 4 and 5 (Ellingwood et al. 2007).

$$[4]\ P[DS\,|IM] = \Phi\left[\frac{1}{\beta_{DS}} ln\left(\frac{IM}{IM_{DS}}\right)\right]$$

$$[5]\ \beta_{DS} = \sqrt{\beta_D^2 + \beta_c^2 + \beta_M^2}$$

IM_{DS} is median value of the intensity measure *IM* at which the building reach the threshold of damage state *DS*; β_{DS} is the log normal standard deviation the *IM* for damage state *DS*, and Φ is a standard normal cumulative distribution function; β_D, represents the uncertainty in seismic drift demand; β_C represents the uncertainty in the threshold drift capacity (ISD_{DS}) of a specific damage state and β_M represents the uncertainty in the modelling. For simplified fragility analysis, default values can be assumed for each log normal standard deviation. In this study, β_D is assumed to be equal to 0.3 based on the results of time history analysis database (see section 2); β_C is assumed to be equal to 0.25 and β_M to 0.2 as recommended by (Ellingwood et al. 2007). For ductile reinforced concrete frame buildings, Hazus (FEMA, 2013) damage state definitions and median drift threshold capacity values were adopted as shown in Table 3. Using Equations 1 to 3 and substituting for the values of ISD_{DS} for each damage state, the median IM_{DS} corresponding to each damage state can be estimated. A numerical example is provided in the next section.

Table 3: Damage state definitions for ductile reinforced concrete frames (FEMA, 2013).

Damage state	Damage description	Drift threshold (ISD_{DS})
Slight	Flexural or shear type hairline cracks in some beams and columns near joints or within joints.	0.25%
Moderate	Most beams and columns exhibit hairline cracks. Some of ductile frame components have reached yield capacity indicated by larger flexural cracks and some concrete spalling.	0.5%
Extensive	Some ductile frame components have reached their ultimate capacity indicated by large flexural cracks, spalled concrete and rebar buckling.	1.5%
Complete	Structure is collapsed or in imminent danger of collapse.	4%

4 CASE STUDY

In order to demonstrate the application of the proposed seismic demand model for fragility analysis of frame buildings, the simplified fragility analysis method is applied to a case study of a 16-story ductile reinforced concrete frame building (Figure 3a) that was designed according to the 2005 NBCC (NRCC, 2005) (Lin 2008).For this frame, fragility functions were not developed in the reference (Lin, 2008) and only the results of incremental dynamic analysis were available. The frame was designed for Vancouver which is in a high seismic hazard zone in Canada. The design base shear was calculated using the seismic design spectrum for Vancouver. The foundations were assumed to be on stiff soil represented by site class C in NBCC. The resulting base shear coefficients (V/W, where V is the base shear and W is the seismic weight) for the frame was 0.035. Compressive strength of concrete f_c = 30 MPa, and yield strength of reinforcement f_y = 400 MPa were used in the design. The estimated fundamental period was 2.75 sec. The dimensions of the beams and columns, and the reinforcement obtained from the design are given in Lin (2008). For T_1 equals 2.75 sec, the corresponding C coefficient is computed from Equation 3 and is equal to 2.57. The $Sa(T_1)$ corresponding to each ISD threshold is computed using Equations 1 and 2 as shown in Table 4. Using Equation 5 and substituting for β_D equals 0.3, β_C equals 0.25 and β_M equals 0.2, the log normal standard deviation (β_{DS}) of all damage states was 0.45. The fragility functions are developed as shown in (Figure 3b) using Equation 4 with median $IM=Sa(T_1)$ as calculated in Table 4 and the a standard deviation of β_{DS} = 0.45. The estimated median Sa(2.75s) for slight, moderate, extensive, complete damage was: 0.03g; 0.06g; 0.18g and 0.48g, respectively. These functions can be used to evaluate the seismic vulnerability for variable IMs corresponding to different earthquake scenarios.

Table 4: The median ISD and the corresponding Sa(T_1) for each damage state.

	$ISD_{(DS)}$	Sd(T_1) (m)	Sa(T_1) [g]
Slight	0.25%	0.06	0.03
Moderate	0.50%	0.11	0.06
Extensive	1.50%	0.34	0.18
Complete	4.00%	0.91	0.48

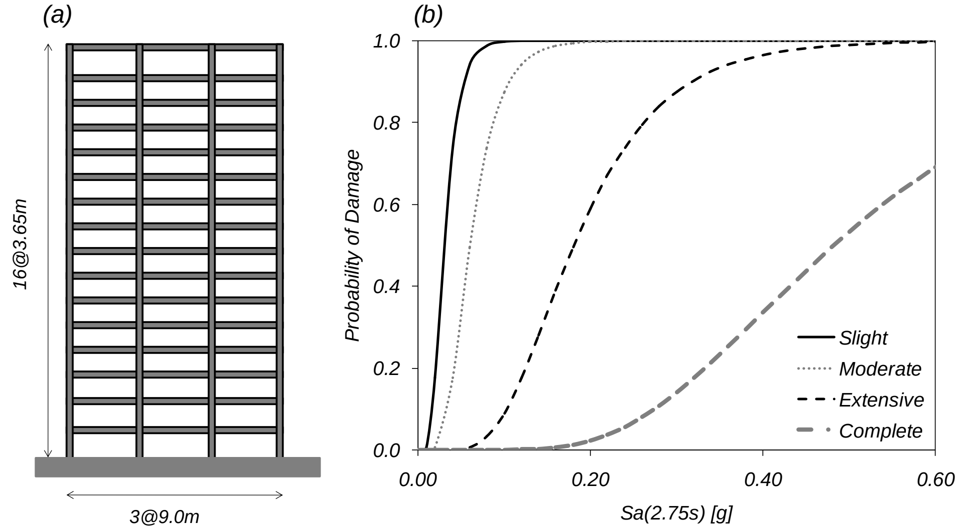

Figure 3: (a) An elevation view of the 16-story ductile reinforced concrete frame and (b) the corresponding fragility functions using the simplified seismic demand model.

The developed fragility functions are then used to evaluate the seismic vulnerability of the case study frame for seismic hazards at Vancouver corresponding to the most recent 2015 NBCC values (NRCAN 2015) for 2% and 10% probability of exceedance (PE) in 50 years. The corresponding Sa(2.75s) for 2% and 10% in 50 years are: 0.2g and 0.09g, respectively. At the traditional 10% PE in 50 yr earthquake hazard level that would have been deemed to be appropriate for ordinary buildings, the response of the frame satisfied the life-safety performance objective with the moderate damage as the most probable post-earthquake damage state (76%) and with 6% probability of extensive structural damage. At the design level seismic hazard (2% in 50 years), the frame response satisfied the collapse prevention performance objective where there is a low probability of complete damage (2%) at that design level hazard. For regional seismic risk studies, similar fragility functions can be derived for a database of buildings using the period-height relationships to provide rapid estimates of the seismic damage for a given seismic intensity.

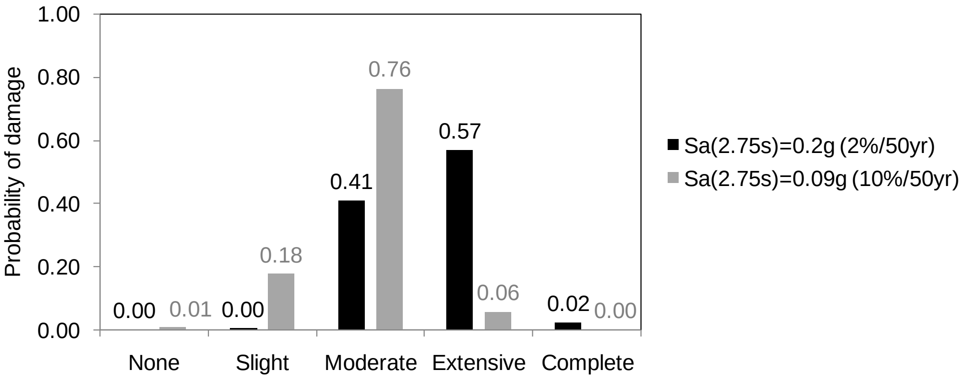

Figure 4: The estimated probability of damage corresponding to the 2% and 10% probability of exceedance in 50 years for the 16-story case study frame located in Vancouver.

5 PRACTICAL APPLICATION OF THE METHOD

The proposed seismic demand and fragility methods in this paper are mainly developed for regional scale seismic risk assessment studies and the evaluation of the seismic vulnerability of a portfolio of buildings. The objective is to provide first-order estimates of the vulnerability of existing buildings with reduced computational effort. The outcomes of such estimates can provide rapid post-earthquake damage assessment for emergency response shortly after a strong earthquake event and to identify thresholds (based on damage probability) for decisions related to the evacuation or potential long-term closure of the building for repairs. Moreover, pre-earthquake planning of a portfolio of buildings can be conducted using the proposed method to identify most vulnerable buildings (based on the damage probability) that would require more detailed engineering analysis. For RC-MRF designed for ductility according to modern building codes in this study, it has been shown that the maximum drift is well correlated to the fundamental period of the building. Therefore, for a given region, the combination of a database of a period-height relation of RC-MRF with the inventory of buildings can provide rapid estimates of the drift demand for a given seismic intensity. The inventory of the buildings would require information about the year of construction (to infer the seismic design level) and the height of the building (to infer the fundamental period). First-order fragility functions using the proposed method can be developed for the inventory of buildings using the fundamental period as the main parameter for the estimation of drift demand and the corresponding damage without the need for detailed structural analysis of each building. For an earthquake event in a specific region, the recorded seismic intensity (e.g. special acceleration) can be estimated from shake-maps (e.g. from Geological Survey Canada website) and the corresponding probability of damage states can be estimated using the pre-generated fragility functions of the inventory of buildings.

6 CONCLUSIONS

Fragility functions combine a probabilistic seismic demand model and a probabilistic damage model. The probabilistic seismic demand model correlates a seismic intensity measure (IM) such as the spectral acceleration at the fundamental period of the building, $Sa(T_1)$, to an engineering demand parameter EDP that better correlates with damage such as the maximum inter-story drift. The probabilistic damage model correlates the EDP to threshold damage states (e.g. slight, moderate, extensive, and complete). This paper presented the development of a new simplified probabilistic seismic demand model applicable for fragility analysis of ductile medium and high rise modern reinforced concrete moment resisting frame buildings. The model provides a direct correlation between the maximum inter-story drift to the $Sa(T_1)$ using a new period dependent displacement coefficient. A database was compiled from literature sources of maximum inter-story drift seismic demand predictions using nonlinear finite element models for ductile RC-MRF that were subjected to increasing levels of ground motion intensities. The model was applied to develop fragility functions for a case study ductile 16-story high-rise RC-MRF building that conforms to the provisions of the 2005 National Building Code of Canada. The proposed simplified fragility analysis procedure is particularly useful for the evaluation of the seismic vulnerability of a portfolio of buildings for regional scale risk studies. First-order fragility functions using the proposed method can be developed for the inventory of buildings using the fundamental period as the main parameter for the estimation of drift demand and the corresponding damage.

7 ACKNOWLEDGEMENTS

The authors are grateful for the support provided by the Natural Science and Engineering Research Council of Canada and by the École de technologie supérieure, Montreal.

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