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A DISPLACEMENT-BASED PERSPECTIVE FOR THE CANADIAN CODE SEISMIC DESIGN SPECTRUM

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ABSTRACT

Canadian seismic code provisions are in constant process of development and evolution. Code upgrades are normally based on lessons learned from major events and research. One of the major developments in seismic design over the past decade has been the increased emphasis on performance-based engineering. Code design spectrum of the National Building Code of Canada (NBCC, 2005) for a selected locality is reconstructed in a spectral format based on yield displacement as the main design parameter. The presentation of the generated spectrum is evaluated and compared with the 1995 NBCC provisions. The application of the generated spectrum in performance-based design is explored and illustrated in a step towards the development of codified performance-based seismic guidelines.

Introduction

In general an efficient seismic design should ensure that the structure possesses appropriate strength, stiffness, and ductility to resist given earthquake demands. It is the design approach adopted by codes that delineate the extent of each of these characteristics and thus portray a certain design philosophy. One of the major developments in seismic design over the past 10 years has been increased emphasis on performance based design (PBD) (Priestley, 2000). Performance-based earthquake engineering (PBEE) implies design, evaluation and construction of engineered facilities whose performance when subjected to normal and extreme loads satisfies diverse needs and identified objectives. Two aspects are important in the context of developing PBEE frameworks: seismic hazard and performance. The 2005 edition of the NBCC focuses on updating hazard in spectral formats. The provisions address seismic performance of buildings in terms of both structural and nonstructural damage due to ground motions, with drift being defined as an acceptable measure of structural damage. The drift is calculated at the end of the design process. In effect the design process is a force-based procedure with an additional displacement check.

The formulation of a design methodology that directly addresses performance criteria at an early stage as well as realistic quantification of the nonlinear response of the structure is thus deemed crucial. Recently, several conceptual frameworks for PBEE have been developed (SEAOC, 1995; FEMA, 1997; ATC-40, 1996). Performance objectives are statements of acceptable performance of the structure (Ghobarah, 2001). Limits related to several response parameters may define performance targets. Such response parameters include: stresses, strains, displacements and accelerations. Performance-based seismic

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assessment of structures needs to be investigated from a reliability-based perspective. Thus, defining seismic hazard within any PBEE framework is essential for determining earthquake design levels. The design levels are expressed in terms of mean recurrence interval or probability of exceedence. Seismic mapping served in defining seismic hazard levels for different seismic regions. The clear definition of seismic hazard is important as reflected by the current interest in developing uniform hazard seismic maps.

Being iterative in nature, an effective design process should rely upon relatively stable parameters that are assumed a priori. Several investigations evaluated the stability and suitability of yield displacement as a design parameter for seismic applications (Priestley 2000, Aschheim and Black 2000 and Aschheim 2002). The yield displacement of a structure depends on parameters that are known early in the design process. Furthermore, the kinematics of yield reveals its independence of the lateral strength of the system to a large extent. This inspired the idea of introducing new spectral representations for seismic design that rely on the structure's yield displacement as a design parameter rather than its fundamental period (Aschheim and Black 2000). The strength of the system can be selected based on its yield displacement estimate to achieve a desired performance. Defining performance limit states based on member or system damage levels can be in turn linked to displacement response quantities (Ghobarah, 2004). Therefore within a performance-based framework, yield displacement representations appear to be promising.

The objective of this study is to investigate the use of inelastic yield displacement spectra representations for PBD. The design spectra of the 1995 and 2005 NBCC for a selected locality are reconstructed in a yield displacement spectral format. Due to the complexity that would be associated with constructing an inelastic spectrum based on uniform hazard concept, only the elastic design spectrum of the 2005 NBCC for the selected locality is reconstructed in a yield displacement spectral format. Whereas, the design spectrum of the 1995 NBCC provisions for the same locality is reconstructed in the yield displacement inelastic spectral format. The application of the generated spectra in performance-based design is explored and illustrated in a step towards the development of codified performance-based seismic guidelines. The presentation of the generated spectrum is evaluated within a comparative framework.

Yield Displacement Spectra

In earthquake engineering practice, design using response spectrum method depends on the natural period of vibration as the main characterizing parameter of the structure. This focus on the natural period followed the generally accepted assumption that the strength and stiffness of lateral force resisting elements (LFRE) are independent parameters. However, several recent investigations pointed out that the strength and the stiffness of several LFRE are rather dependant as shown in Fig. 1 (Priestley 2000; Tso and Myslimaj 2003). This interdependency highlighted the problems associated with using the fundamental period as the main parameter in seismic design. Furthermore, it drew the attention to the yield displacement as an appropriate alternative to the period.

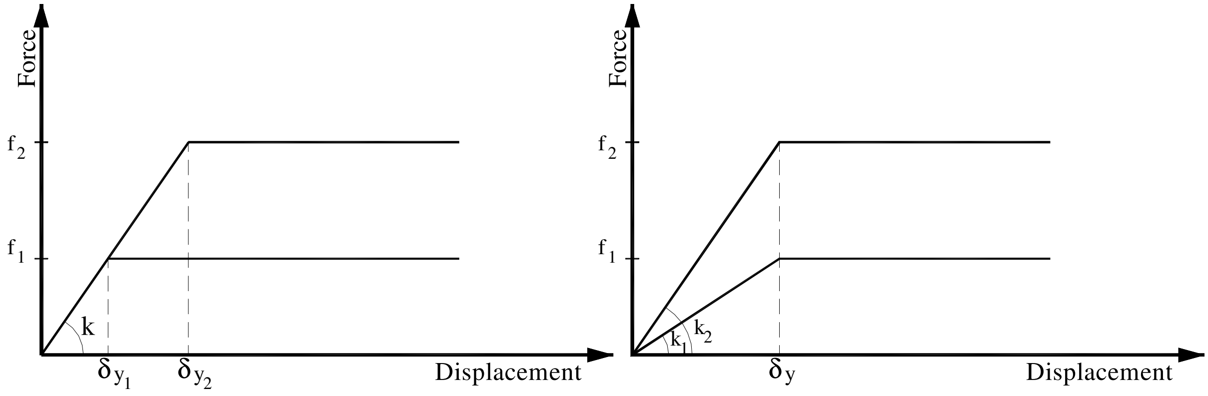
First presented by Aschheim and Black (2000), the yield point spectrum resembled a constant ductility response spectrum (CDRS) in which the yield strength coefficient C_y is plotted as a function of the system's yield displacement u_y. Figure 2 shows the yield displacement spectrum (YDS) of a single degree of freedom (SDOF) system subjected to the El Centro (II-IVLY-RTH6) time-history. Detailed characteristics for this record and other records used in the study are presented in Table 1. The oscillator has an elastic-plastic load-deformation relationship with no post yield stiffness. Viscous damping is taken 5% of the critical damping. The spectra were constructed for constant displacement ductility levels of 1, 2, 3, and 4. Each point on a certain constant ductility curve, corresponds to an oscillator with a given period, yield displacement and strength. Each curve was generated for 401 initial periods, ranging from 0.025 to 10.025 seconds with an interval of 0.025 seconds. The spectrum was plotted twice for both linear and logarithmic scales as shown in Figs. 2a and 2b, respectively.

When plotted using linear scale, periods appear on lines radiating from the origin. On logarithmic scale periods appear as parallel lines sloping at +45°. The logarithmic representation appears to be useful in characterizing different systems, especially in the intermediate and long period range.

Table 1. Selected earthquake records.

Original records: Set S1											Set S2 Synthetic Records*
Subgroup (SG)	Theme	Earthquake		Mw	Station	F.Dist (Km)	Comp.	PGA (g)	A/V	ID	
I	High (A/V)	San Francisco	1957	5.25	Golden Gate Park	11	S80E	0.105	2.28	I -SFCO-RTH1	-BCSTH1
		Lytle Creek	1970	5.40	Wrightwood, CA	15	S25W	0.198	2.06	I -LCRK-RTH2	-BCSTH2
		San Fernando California	1971	6.40	Lake Hughes, St4	26	S21W	0.146	1.72	I -SFDO-RTH3	-BCSTH3
		Central Honshu Japan	1971	5.50	Yoneyama Bridge	27	TRANS	0.151	2.56	I -CHJP-RTH4	-BCSTH4
		Near E. Coast of Honshu	1972	5.80	Kushiro	33	N00E	0.146	2.43	I -NEJP-RTH5	-BCSTH5
II	Intermediate (A/V)	Imperial Valley California	1940	6.60	El Centro	8	S00E	0.348	1.04	II-IVLY-RTH6	-BCSTH6
		Kern Kounty California	1952	7.60	Taft Lincoln Sc.	56	N21E	0.156	0.99	II-KKTY-RTH7	-BCSTH7
		San fernando California	1971	6.40	Lankershim Blvd.	24	S90W	0.150	1.01	II-SFDO-RTH8	-BCSTH8
		Near E. Coast of Honshu	1974	6.10	Kashima harbor	38	N00E	0.070	0.97	II-NEJP-RTH9	-BCSTH9
		Mexico Earthquake	1985	8.10	El Suchil, Guerrero	230	S00E	0.105	0.91	II-MXCO-RTH10	-BCSTH10
III	Low (A/V)	Long Beach California	1933	6.30	Subway terminal	59	N51W	0.097	0.41	III-LBCH-RTH11	-BCSTH11
		Lower California	1934	6.30	El Centro	58	S00W	0.160	0.77	III-LCAL-RTH12	-BCSTH12
		Morgan Hill	1984	6.20	Halls Valley	2.40	240	0.312	0.79	III-MGNH-RTH13	-BCSTH13
		Near E. Coast of Honshu	1968	7.90	Muroran Harbor	290	N00E	0.226	0.68	III-NEJP-RTH14	-BCSTH14
		Mexico Earthquake	1985	8.10	Zihuatenejo	135	S00E	0.103	0.65	III-MXCO-RTH15	-BCSTH15
IV	NF Fault-normal	Northridge	1994	6.70	Rinaldi	7.50	FN	0.889	0.51	IV-NRDG-RTH16	-BCSTH16
		Landers	1992	7.40	Lucerne	1.10	FN	0.714	0.53	IV-LRDS-RTH17	-BCSTH17
		Kobe	1995	6.90	Takatori	4.30	FN	0.786	0.45	IV-KOBE-RTH18	-BCSTH18
		Erzincin	1992	6.70	Erzincin	2.00	FN	0.432	0.36	IV-EZCN-RTH19	-BCSTH19
		Loma Prieta	1989	7.00	Los Gatos	3.50	FN	0.718	0.42	IV-LPTA-RTH20	-BCSTH20
Scaled records: Set S3	IV(0.1755)	Subgroup IV records scaled to PGA=0.1755								IV(0.1755)-NRDG-RTH16 IV(0.1755)-LRDS-RTH17 IV(0.1755)-KOBE-RTH18 IV(0.1755)-EZCN-RTH19 IV(0.1755)-LPTA-RTH20	
Set S4 combines S2 with subgroup IV(0.1755)											

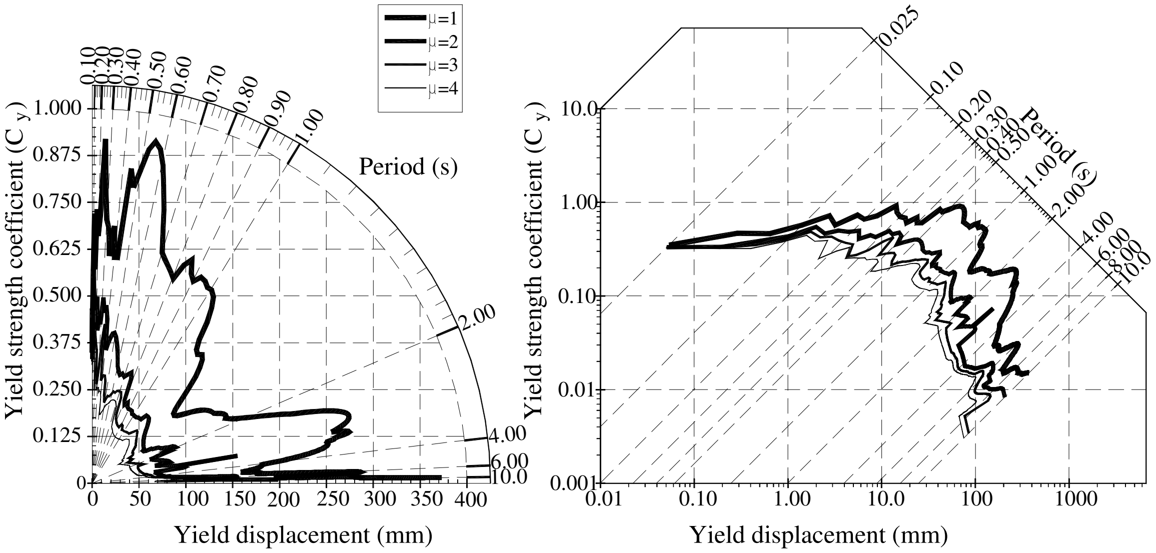
* S2: Set of synthetic records compatible with NBCC 1995 design spectrum.



a) Strength-Stiffness independent element

b) Strength-Stiffness dependent element

Figure 1. Behaviour of lateral force resisting elements.



a) Linear scale.

b) Logarithmic scale.

Figure 2. Yield displacement spectrum of the El Centro (II-IVLY-RTH6) time-history.

Canadian Code Spectrum in the Yield Displacement Spectral Format

The design philosophy of the current Canadian code is strength-based. The 2005 edition of the NBCC contained major changes to the seismic provisions (Heidebrecht, 2003; Adams and Atkinson, 2003; Adams and Halchuk, 2003). They included updated hazard in spectral format, change in return period, period-dependant site factors, delineation of effects of overstrength and ductility amongst other changes. A major change related to demand spectra representations is to define hazard in the form of uniform hazard spectra (UHS). Further, the new seismic code provisions are based on using 2% probability of exceedence in 50-year seismic hazard values. However, the seismic design philosophy reflected by the new code is still strength-based. Estimated values of the structural period are the main design parameters with drift calculations at the end of the design process. The design sepctrum given by the NBCC (1995) is shown in Fig. 3 for a building location at Victoria, B.C. A zonal velocity ratio value of 0.3 and a foundation factor value of 1.3 were considered. Seismic hazard parameters for Victoria B.C. were calculated with 10% in 50-year probability of exceedence and 84 percentile values considered. Importance factor, foundation factor, site response factor and force modification factor were estimated to match assumptions made previously to calculate base shear coefficients by the NBCC (1995) for the same site location.

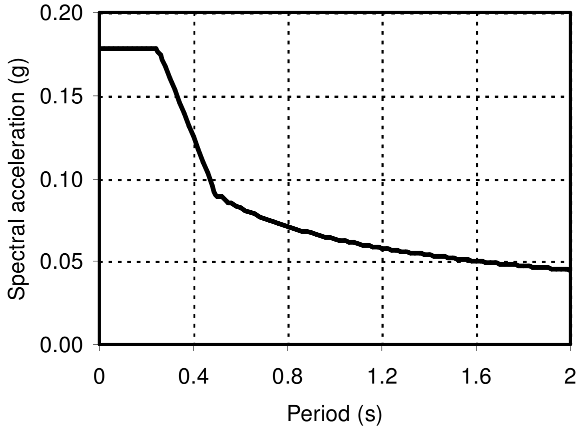


Figure 3. The 1995 NBCC design spectrum for Victoria, B.C.

In this section, the procedure for transforming the code spectrum into the yield displacement spectrum format is described as a step towards the development of codified performance-based seismic guidelines. A set of 20 earthquake records labeled (S1) was selected for use in this part of the study. The records were subdivided into 4 distinct subgroups. The first three groups of 5 records each, were classified according to the (A/V) ratios; being high, intermediate, and low. Whereas the last subgroup contained near-fault earthquake (NFE) records from major earthquakes with forward directivity effects. Using the fault normal component of these records was intended to investigate the effect of introducing pulse-like motions in the construction of the design spectra. Table 1 lists the records used in the study. To reconstruct the design code spectrum in the new format; a set of synthetic time histories: (S2) is generated from the (S1) set of records to be compatible with the NBCC (1995) design spectrum. The artificial time histories were constructed using the computer software SYNTH (Naumoski, 1985). This program utilizes spectral acceleration input for various periods to construct a time-history that would produce such a response spectrum.

The five NFE records were selected representing fault-normal components in the forward directivity zone. The records are labeled subgroup IV (SGIV). It was recognized that the process of generating the synthetic time histories from the (SGIV) subgroup records modified the amplitude of the pulse by reducing it in the resulting time histories. To investigate the forward directivity effects on the process; the original records of the (SGIV) subgroup were scaled to 0.1755g peak ground acceleration (PGA) level, representing the PGA for the NBCC (1995) design code spectrum. The plots of the scaled records maintained the properties of the original near-fault records, in the form of the low frequency pulses in the velocity time histories. However, the spectra of the scaled records were a poor fit with the code spectrum.

Figure 4 shows the mean yield displacement spectra for the set of synthetic records (S2). Base shear coefficient values were calculated according to the NBCC (2005) provisions and were compared to the mean YDS of set of records S2 in Fig. 4. The effect of including near-fault records was investigated by comparing the mean of yield displacement spectra for the scaled set of records SGIV (0.1755) with the mean yield displacement spectra of the (S2) set of synthetic records and the 2005 NBCC spectrum as shown in Fig. 5. For further investigation of the effect of the near-fault records, mean yield displacement spectra including near-fault effects are compared with the set that does not include the near-fault records in Fig. 6.

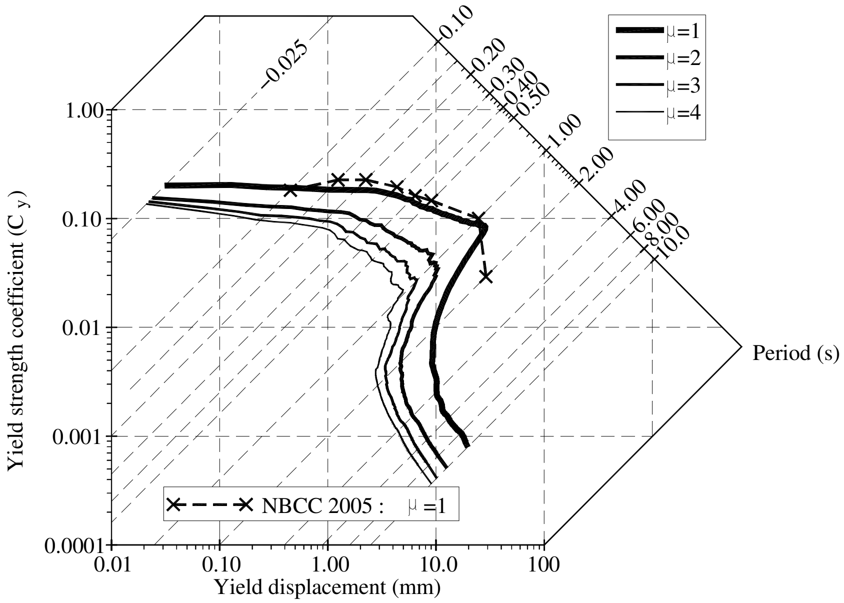


Figure 4. Mean yield displacement spectrum for record set S2 compared to the 2005 NBCC spectral values.

Figure 4 shows that values given by the 2005 NBCC exceed the demand values given by the NBCC (1995) for the location and set of factors considered. Figures 5 and 6 show the higher demand over a wide range of vibration periods under the near-fault ground motions. It is observed that the NBCC 2005 spectrum is closer to the NFE spectra than that of the NBCC 1995. However, the values of displacement and strength demands for near-fault ground motions exceed the minimum values given by the 2005 edition of the NBCC over the intermediate and long period range.

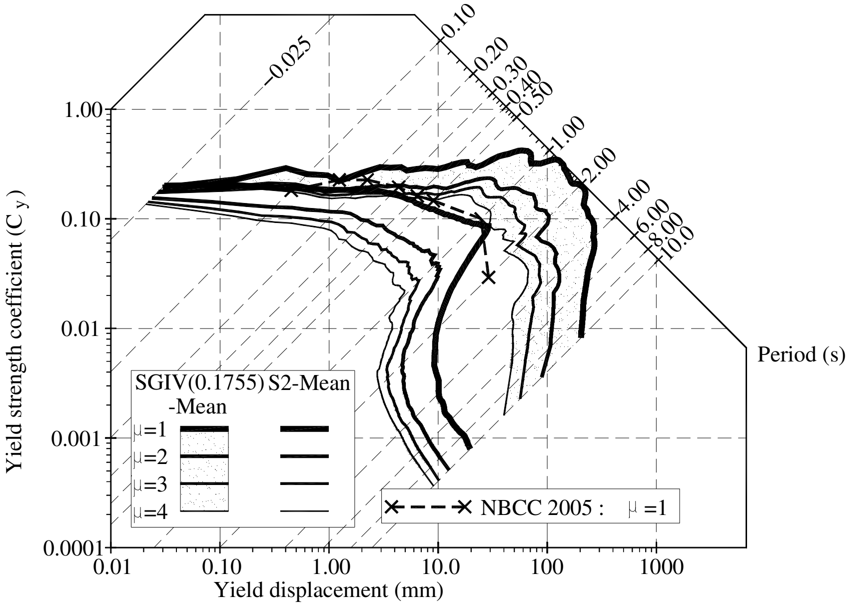


Figure 5. Mean yield displacement spectrum for record sets SGIV(0.1755) and S2 compared to the 2005 NBCC spectral values.

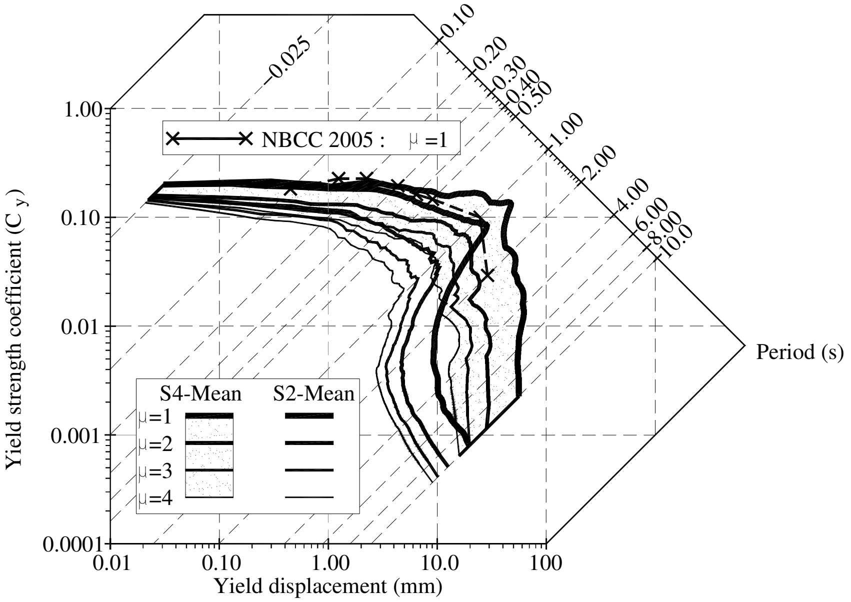


Figure 6. Mean yield displacement spectrum for record sets S4 and S2 compared to the 2005 NBCC spectral values.

Applications of Yield Displacement Spectral Representation

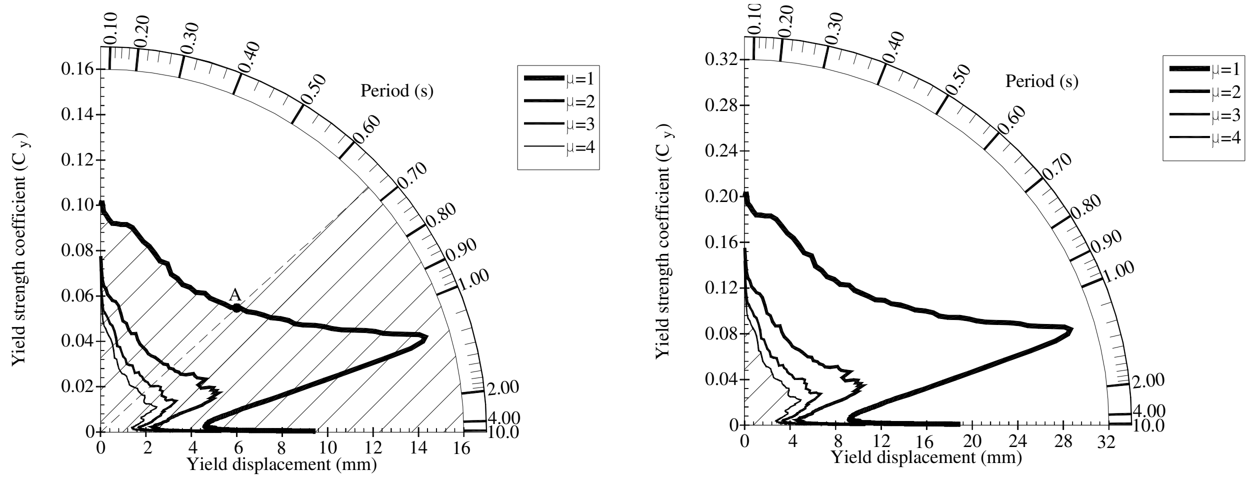
Estimating the peak displacement of structures under seismic excitations is of interest in the design process. In the performance-based design procedure, it is required to determine the structural properties to control its performance over various seismic hazard levels. Designing the structure to meet predetermined performance objectives is expected to reduce economic losses due to structural and nonstructural damage. The design process can be performed using the yield displacement spectra. Using equivalent SDOF models for multistory buildings limits both applications to uniform structures with response dominated by the first mode of vibration. However, the merit of using yield displacement spectra appears in its applicability to performance-based design. Different performance levels combined with different earthquake hazard levels can be incorporated. The resulting performance objectives can be checked out in analysis applications, and can be used to determine combinations of lateral strength and stiffness that limit drift and displacement ductility in design applications. Estimated yield displacement for the structure's equivalent SDOF system is used to determine the required strength for seismic design. A case study is presented to illustrate the use of yield displacement spectra in performance-based engineering.

A single-story building with height of 3m is considered. Figure 7 summarizes the desired performance and earthquake hazard levels. Drift limits given by the Ghobarah (2004) are used with assumed displacement ductility limits to construct admissible design regions on the YDS representations. The 1995 Canadian code lacks provisions for scaling design spectra for various earthquake hazard levels. Therefore, data given by the ATC (1996) document was used in guiding values for this process. Serviceability Earthquake (SE) spectrum was scaled to 0.50 the PGA of the Design Earthquake (DE) hazard level. Whereas, Maximum Earthquake (ME) spectrum was scaled to 1.50 the PGA of the (DE) hazard level. For this case study, the YDS previously constructed for the NBCC (1995) design code was used to define the (DE) hazard demand. Fig. 8c shows the admissible design regions for the different performance levels, and the combined performance objective. The unshaded areas give the admissible regions on the YDS. Systems lying within the shaded areas either violate drift or ductility limits for the assigned performance objectives.

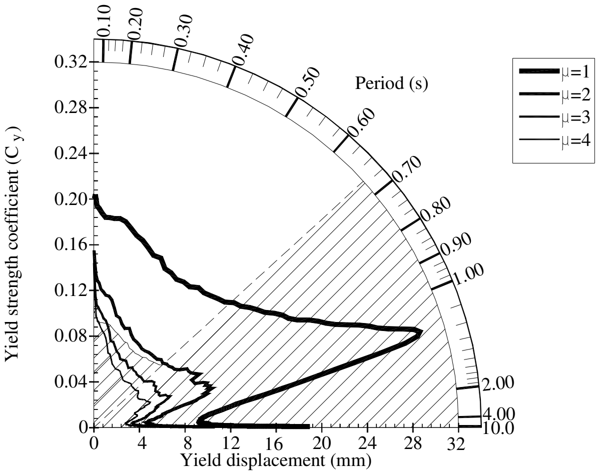
Objectives		▨ Minor damage	Repairable damage	▨ Irreparable damage	Severe damage
Earthquake Hazard	▨ SE	▨			
	▨ DE			▨	
	ME				
Drift limit Ductility limit		<0.2% 1	<0.5%	<1.5% 4	<2.5%

Figure 7. Performance objectives for case study.

For minor damage performance level with SE hazard level, the drift is limited by 0.2%. For ductility of 1, the system is required to behave elastically. Thus, the limiting yield displacement for the given system is 6 mm. Admissible design region for this performance level is illustrated in Fig. 8a. On the right hand side of point (A), the limiting parameter is the drift. Whereas, the inadmissible design region on the left is determined on the basis of ductility limit. The shaded area in Fig. 8b defines the un-admissible region for the un-repairable damage performance level. It is totally ductility controlled. The limiting yield displacement is 11.25 mm, which exceeds the values given by the relevant ductility curve. Finally, Fig. 8c combines the information given by both Figs. 8a and 8b. Any system lying in the unshaded area in Figure 8c is expected to meet the adopted performance objectives.



a) Admissible region for minor damage performance level. b) Admissible region for irreparable damage performance level.



c) Admissible region for assigned performance objectives.

Figure 8. Admissible design regions for a single-storey building with height=3m for different performance levels (1995 NBCC generated spectrum considered for design).

Concluding Remarks

Code design spectrum given by the NBCC (1995) for Victoria, B.C. was reconstructed in the yield displacement spectral formats. The effect of introducing near-fault records in constructing the design spectra was investigated. The application of the generated spectra in performance-based design was explored and illustrated in a step towards the development of codified performance-based seismic guidelines. Corresponding values given by the NBCC 2005 were included in a comparative framework. Yield displacement spectra (YDS) appear to be useful tools for seismic analysis and design in a performance-based design framework. Different performance levels combined with different earthquake hazard levels can be incorporated. The resulting performance objectives can be used to determine combinations of lateral strength and stiffness that limit drift and displacement ductility in design applications. The most appealing application for YDS is in multi-performance level based design. Admissible design regions for multi-performance levels can be defined on design YDS through graphical procedures. The methodology for design using YDS appeared to be simple and reliable.

NFE displacement and strength demands exceeded the minimum design requirements given by the NBCC (1995) design code spectrum over the whole range of periods considered. The increase in the NFE response values appeared to be dramatic for intermediate and long periods. The difference between the NFE demands and the NBCC 2005 design requirements remains although reduced.

The NBCC 2005 focused on updating hazard in spectral formats. The provisions address seismic performance of buildings in terms of both structural and nonstructural damage due to ground motions, with drift being defined as an acceptable measure of structural damage. However, the drift calculations at the end of the design process results in a force-based procedure with an additional displacement check. This procedure may be used for one performance criterion but will be impractical in cases of multi-performance criteria. Further development for the code provisions is needed to reflect performance-based engineering approaches.

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