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SERVICEABILITY LIMIT STATE CRITERIA FOR THE SEISMIC ASSESSMENT OF R/C BUILDINGS

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SUMMARY

This paper presents a deterministic study that has as objectives the identification and investigation of various alternative definitions of the serviceability limit state (SLS), in terms of local and global criteria that can be adopted in inelastic, dynamic, time-history structural analysis. Following a state-of-the-art review, several SLS criteria are considered and compared, mostly by means of calculating the accelerogram scaling factors that are necessary for attaining these criteria when a typical building frame is loaded by natural earthquake ground motions. In line with previous studies, a lack of consistency is observed, as it is found that the results are highly sensitive to the assumed SLS criterion.

INTRODUCTION

The use of limit states in structural design is a meaningful way of safeguarding against several unfavorable scenarios, such as excessive construction cost, inadequate safety and unnecessary future repair costs. In modern design codes of practice, unlike the ultimate limit state (ULS), the serviceability limit state (SLS) aims to minimize any future structural damage due to relatively low, and not unexpected, forces. Even though the concept of the SLS is well appreciated internationally, its definition in structural design and assessment remains a somewhat unresolved matter. This is particularly important in seismic applications whereby it is essential to strike the right balance between adequate safety and non-excessive expenditure, whilst the nature and magnitude of the seismic loads are highly uncertain.

Serviceability limit states relate to structural performance under normal service conditions, as for serviceability the function of a building, its appearance, maintainability, durability and comfort for its occupants must be preserved under normal use. Thus, the SLS should relate to conditions that are to be met for normal use and durability of the structure. As indicated by DiPasquale & Cakmak (1988), since serviceability does not really refer to structural safety, design recommendations with respect to SLS criteria are mainly based on past experience. Moreover, as structural response at either global or local level generally relates to strength, stiffness and deformation capacity, the SLS needs to be defined using

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meaningful parameters that would lead to damage levels that are consistent with the actual definition in the code under consideration.

In many cases, SLS criteria need to be defined whilst bearing in mind the targeted function of the structure and, thus, the expectations of prospective occupants or developing authorities. However, it is implied in all cases that SLS criteria should be attained during elastic structural behavior, when damage indicated by, for example, cracking or deformation, is still relatively low. Hence, in establishing SLS criteria, it is necessary to consider the overall design philosophy, especially as nowadays structures are permitted, and indeed expected, to behave in an inelastic, ductile manner during earthquakes of considerable intensity. Furthermore, SLS criteria ought to, ideally, allow for different materials, including high strength materials, as well as different construction systems and practices.

As part of the overall procedure for earthquake-resistant structural design when limit states are used, it is also necessary to identify the serviceability earthquake. However, this is another issue that deserves attention as assumptions often significantly vary amongst codes. For instance, Wen (2001) pointed out the excessive degree of conservatism that is associated with a serviceability earthquake corresponding to a 50% probability of exceedance in 30 years, which can end up controlling the design. Other frequently used descriptions of the serviceability earthquake are closer to a 10% probability of exceedance in 10 years (e.g. Eurocode 8). This corresponds to an earthquake of a return period of 95 years, whereas a 50% probability of exceedance in 30 years corresponds to a return period of 44 years and is therefore a more conservative assumption. Nevertheless, the current paper focuses on criteria for describing the degree of damage that is expected to occur prior to the attainment of the SLS, thus the serviceability earthquake is considered only to a limited extent herein.

Following this brief introduction, the current paper presents an overview of the way in which the SLS is treated in modern codes for earthquake-resistant structural design. This enables the selection of SLS criteria that are then used in a parametric study concerning the seismic performance of a 10-story reinforced concrete (R/C) frame. The overall scope and aims of this study are the investigation of alternative SLS criteria and a demonstration of the effect that the selected criteria might have on structural assessment.

DEFINITION OF THE SLS: A STATE-OF-THE-ART SUMMARY

Modern Seismic Design Codes

Following the development of limit state design, many modern design codes, including ones accounting for earthquake resistance, adopt such a design approach. Countries whose seismic codes are based, even partly, on limit state design include Bulgaria, Canada, Iran (for R/C design only), Japan, Mexico (Mexico City Code), New Zealand, Portugal, Russia, Spain, Switzerland and Venezuela. Moreover, this list should also include European countries that have adopted Eurocode 8 (EC8). Most commonly, both the ultimate and serviceability limit states are allowed for, even if alternative names are used for these. For instance, the National Building Code of Canada (1995) specifies one state that governs gravity load deflections and serviceability, whereas a more severe limit state governs strength and resistance. Nevertheless, SLS criteria vary from code to code. Bertero et al. (1991), by considering various seismic codes, arrived at the conclusion that recommended limiting interstory drifts vary between 0.06 and 0.6%. Due to the recent revision of many such codes, this range would now be expected to be even wider.

According to the New Zealand code NZS 4203:1992, for the SLS deflections must not lead to damage that can cause loss of function of a structure. In addition to this general requirement for all design scenarios, in Part 4 of this code the earthquake provisions further state that for the SLS there must be adequate strength and stiffness, whereas adequate strength, stiffness and ductility are required for the ULS. On the other hand, the Bulgarian Code for the design of buildings and structures in seismic regions (1987) states that the SLS aims to limit damage to buildings due to earthquakes, whereas the ULS aims to provide integrity and residual capacity in case an "extraordinary" earthquake strikes.

The European design code for seismic resistance of structures, EC8 (CEN, 2003), allows for serviceability through a "damage limitation" limit state, whilst ultimate limit state provisions are also included. The damage limitation limit state aims to satisfy the stated requirement that *"the structure shall be designed and constructed to withstand a seismic action having a larger probability of occurrence than the design seismic action, without the occurrence of damage and the associated limitations of use"* and corresponds to a state beyond which specified service requirements are no longer met. General deformation limits are recommended in terms of a set limiting interstory drifts, as follows:

- 0.5% for buildings with nonstructural elements of brittle materials attached to the structure,
- 0.75% for buildings with ductile nonstructural elements, or
- 1.0% for buildings with nonstructural elements that do not interfere with structural deformations.

However, a reduction factor, ν, is also introduced in order to account for the lower return period of the seismic action corresponding to the damage limitation requirement. Although each country adopting EC8 is free to specify specific values of ν, recommended values are 0.4 for important classes I and II or 0.5 for important classes III and IV. Moreover, if a structure is of high importance as far as civil protection is concerned, EC8 requires that further checks are carried out in order to ensure that there is sufficient resistance and stiffness so that the structure can remain operational following a seismic event associated with an appropriate return period.

Codes that are applicable to regions where seismicity does not pose a very serious problem are sometimes less demanding in terms of required checks. For example, the Swiss Standard SIA 160 (1989) states that deformations must be determined considering the actions and principles that are considered for verifying structural safety, but for serviceability it requires that limiting interstory drifts are only checked for structures of class III, which covers structures whose function is vital to the infrastructure or ones whose damage would be associated with considerable environmental risk.

Recent Research

Overall, there appears to be lack of published research that focuses on aspects relating to the SLS, whereas the ULS is a more popular issue. This has also been pointed out by Quan & Gengwei (2002) with respect to structural reliability studies, who rightly point out that the importance of the SLS is highlighted by the relatively high frequency of serviceability "failures" that occur and the large economic losses associated with these.

In defining SLS criteria for research purposes, the interstory drift is by far the most commonly used parameter, although appropriate threshold values are not readily available. As Table 1 shows by means of several examples, different researchers adopt different limiting values. Nonetheless, although it is generally recognized that the overall degree of deformation offers an indication of the degree of damage sustained by structural members, the types of deformations primarily responsible for damage to nonstructural components remain rather vague, which can be a worrying issue, at least as far as the SLS is concerned. Mahin (1976), for example, noted that lateral displacement ductility factors can generally provide a good indication of structural damage, whereas they do not adequately reflect damage to nonstructural elements. Nonstructural damage is more dependent on the relative displacements (interstory drifts) than on overall lateral displacements, so that earthquake-resistant design ought to provide for both of these.

Foschi et al. (2002), in an example to demonstrate a newly proposed approach for reliability and performance-based design, assessed the serviceability of a twenty-story building of height 80m using three criteria all of which related to lateral story deflections as follows:

(i) a limiting roof drift of 0.05m,
(ii) a limiting interstory drift of the 15^{th} story of 0.067%, and
(iii) a limiting interstory drift of the 5^{th} story of 0.080%.

Table 1. Examples of critical interstory drift values used in the literature for definition of the SLS

Reference	Limiting interstory drift (%)	Notes
Bertero et al. (1991)	0.06-0.6	State-of-the-art range considering various seismic codes.
Bertero et al. (1991)	0.3	Value based on field observations.
Saito et al. (1996)	0.5	First member yielding also selected as an SLS criterion.
Wen et al. (1996)	0.5	First member yielding also selected as an SLS criterion.
Ghobarah et al. (1997)	0.7	Critical value actually defined for the "elastic" limit state.
Mosalam et al. (1997)	0.2-0.5	Limiting value range actually defined for the "insignificant" damage state (repair to nonstructural elements required, only).
Esteva et al. (2002)	0.3	Value recommended for a design earthquake return period of 10 years.

It must be noted, however, that design of this building did not account for seismic loading. Nonetheless, for each of these criteria reliability-based design resulted in different reliability levels, with reliability indices of 2.55, 2.51 and 1.97, respectively. These indices correspond to probabilities of the SLS being attained of 0.0054, 0.0060 and 0.02442, respectively, thus a clear difference in safety levels can be observed. In another example considering seismic loading, Foschi et al. (2002) considered a limiting roof drift of H/100, where H is the total building height. For the aforementioned twenty-building story this would correspond to 0.08m, thus, as expected, allowing for seismic loading usually implies larger allowable deflections, even at the SLS.

Cracking of structural or nonstructural elements would be another suitable way for describing the SLS, as cracks are often visually unacceptable. Particularly considering R/C beams, Quan & Gengwei (2002) employed the maximum crack width as the damage indicator, which also appears in the Chinese code for design of concrete structures in terms of three crack controlling classes. For instance, this code gives a limiting SLS crack width of 0.3mm corresponding to structures that are designed for cracking control class III but for normal indoor environments. As this does not specifically allow for seismic loading, it is anticipated that an appropriate limiting crack width would thus be greater than 0.3mm.

The examples summarized above indicate some key differences in the representation of the SLS adopted for research purposes. These differences are not only in the measures that are used to predict attainment of the SLS, but also in the assumed critical values where identical measures are used.

SEISMIC ASSESSMENT OF R/C FRAMES

Selection of SLS criteria

As has been shown above, there do not appear to be well established and widely accepted criteria for the definition of the SLS, at least as far as the seismic performance of R/C buildings is concerned. Therefore, this paper, through a deterministic study, aims to further demonstrate the differences in structural performance at several states that need to be firstly identified as possible serviceability limits.

Due to the significant change in structural behavior when the inelastic region is entered, this elastic/inelastic boundary may be seen as a meaningful way of representing the SLS. Depending on the adopted structural modeling, attainment of the SLS in such a case would thus be defined at the instance when a yield displacement, yield rotation or yield curvature is exceeded anywhere in the structure. Under capacity design it is of course realized that yielding should initiate in one of the beams, as these are the less critical elements for the overall stability of the structure, hence it is targeted that plastic hinges are primarily formed in beams. Herein, two possible SLS criteria based on member yielding are investigated.

For the first criterion, attainment of the SLS is simply assumed to occur at the instant when any structural element in the frame first yields, or when a plastic hinge forms. For the second criterion, however, the SLS is not attained until a rotation in any structural element reaches twice its yield value.

As the frame to be considered was designed to the original version of EC8 (CEN, 1995), for which the SLS was recommended to correspond to an interstory drift of 0.4% for structures with nonstructural elements of brittle materials or 0.6% when nonstructural elements are fixed so as not to affect structural deformations, an average limiting interstory drift of 0.5% is considered herein as an alternative SLS criterion. However, as mentioned earlier, the current version of EC8 (CEN, 2003) recommends that a serviceability (termed damage limitation) drift of 0.5% be taken only when nonstructural elements of brittle materials are attached to the structure.

Modeling and procedure

Structural analysis is mainly conducted using the program DRAIN-2000 (Kappos & Dymiotis, 2000), which enables dynamic inelastic time-history analysis of two-dimensional structural systems. The structural system considered herein is a ten-story three-bay R/C frame, properly designed and detailed to the initial versions of Eurocodes 2 (CEN, 1991) and 8 (CEN, 1995) for R/C and earthquake-resistant design, respectively. It is noted that this frame is the same as that probabilistically assessed by Dymiotis et al. (1999). However, the research presented herein involves a parametric, deterministic study. For this purpose, three natural earthquake accelerograms are used, which include the popularly used El Centro record obtained during the Imperial Valley earthquake of 1940, and two records taken from the Kalamata (Greece) earthquake of 1986 and the Northridge (USA) earthquake of 1994. These three accelerograms are selected as they feature different characteristics, as presented in Table 2.

The overall adopted procedure involves analyzing the multi-story frame subjected to each accelerogram, as many times as necessary until attainment of the SLS criterion under consideration is achieved. Therefore, this requires scaling of the accelerograms and the scaling factor at first attainment of the considered criterion is recorded, thus enabling comparisons. Scaling is achieved by simply multiplying ground accelerations at all time steps by a factor a_s, where $a_s>0$. For the structural modeling, material properties are assumed to take their mean values ad structural members are assumed to be moderately cracked from the start of the analysis. The latter is not an unrealistic assumption, as some, at least small, degree of damage would be expected to be present in a building when it is loaded by seismic forces. Moreover, an overall lumped mass approach is used for the dynamic analyses.

Results

Initial analyses

Firstly considering the possible SLS criterion of 0.5% maximum interstory drift, Figure 1 shows the interstory drift patterns corresponding to each accelerogram, when this critical value is reached for the first time. The scaling factors required for the three accelerograms EL CENTRO, KALW and NORL are 1.006, 1.225 and 0.351, respectively. It is also pointed out that the critical interstory drift of 0.5% is encountered in the second story when the frame is subjected to NORL, whereas this critical value is firstly

Table 2. Main features of the three accelerograms used

Earthquake	Site & component	Legend	Magnitude	R (km)	A (g)	A/V (g.s/m)	$S_{a,max}$ (g)	$T(S_{a,max})$ (s)	Duration used (s)
Imperial Valley 18/5/40	El Centro S00E	EL CENTRO	7.1	9	0.35	1.04	0.92	0.250	26.5
Kalamata 13/9/86	Kalamata N10W	KALW	6.2	12	0.27	1.15	1.21	0.325	8.5
Northridge 17/01/94	Canyon Road N46E	NORL	6.7	21	0.41	3.50	0.97	0.900	19.5

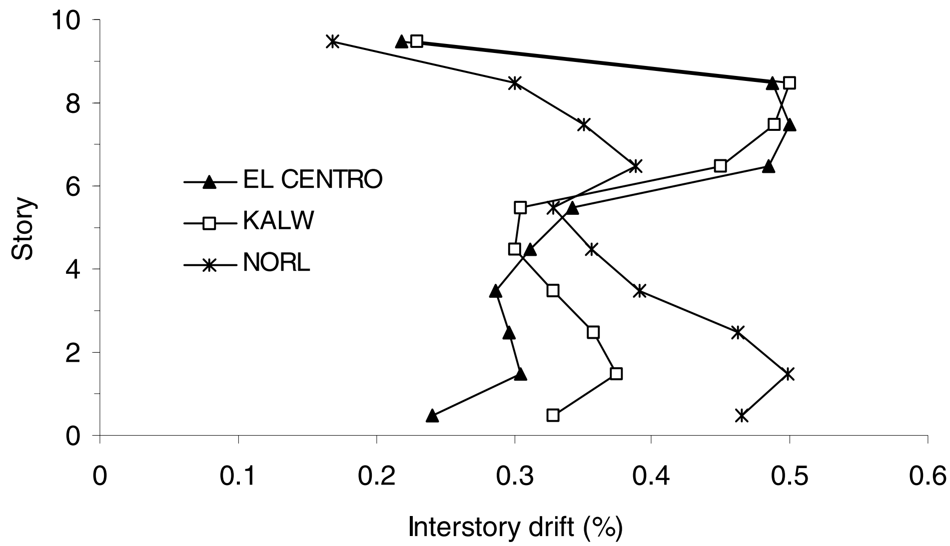

Figure 1. Intestory drift patters when the critical value of 0.5% is first exceeded

reached in the eighth or ninth stories for the other two accelerograms. This is not surprising, however, since NORL exhibits some significantly different characteristics from the other two accelerograms, as is evident from Table 2.

Figure 2 compares the above scaling factors for the attainment of the SLS criterion based on a critical interstory drift of 0.5% with those corresponding to the two yield rotation criteria as previously discussed herein. It is clearly seen that both yield rotation criteria are attained at significantly lower scaling factors, which of course implies that the severity of the seismic ground motion that is required for these two criteria to be attained is a great deal lower. It is also interesting to note that the scaling factors required for the attainment of the two rotation-based criteria are fairly close, despite a difference of θ_y in the critical value. The results shown in Figure 2 are also presented in Figure 3, but now in terms of peak ground accelerations rather than scaling factors. As expected, the general observations with respect to the comparison of the three SLS criteria remain the same. However, it is obvious from this figure that, especially for the El Centro and Kalamata accelerograms, the required peak ground accelerations for the attainment of the different criteria are fairly similar. The generally lower accelerations corresponding to the Northridge accelerogram may be justified by the fact that for a structural period of around 0.95s, which is roughly the vibration period of the frame considered herein, this accelerogram results in a spectral acceleration of 0.93g, whereas EL CENTRO and KALW result in significantly lower equivalent values of 0.53g and 0.24g, respectively.

Further analyses

For the sake of comparison, it is decided to try decreasing the critical interstory drift by increments of 0.1% with the scope of establishing a critical value that shows better agreement with either of the criteria based on the yield rotation. Whereas for a critical interstory drift of 0.3%, $2\theta_y$ is exceeded in at least one structural element for all three accelerograms, when this is reduced to 0.2%, θ_y is exceeded in some elements whereas $2\theta_y$ is never reached. The corresponding interstory drift patterns are shown in Figure 4, with the corresponding scaling factors listed in Table 3 alongside the factors from the initial analyses. There is some obvious resemblance between these drift patterns and those presented in Figure 1, but when the frame is subjected to EL CENTRO the critical drift is now first exceeded in both the second and seventh stories. As far as the scaling factors are concerned, it is interesting to observe that these almost coincide with those required for first exceedance of the yield rotation.

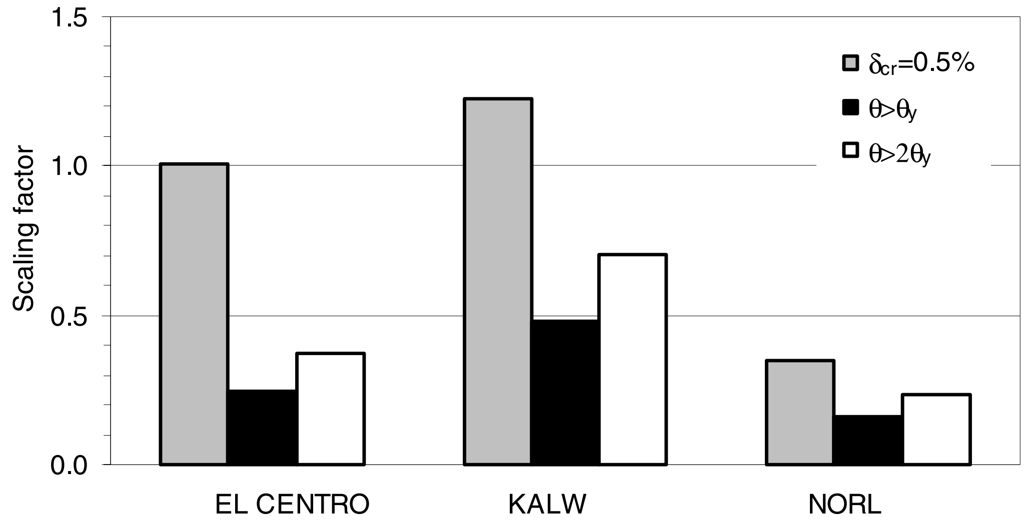

Figure 2. Comparison of scaling factors required for attainment of the different SLS criteria considered

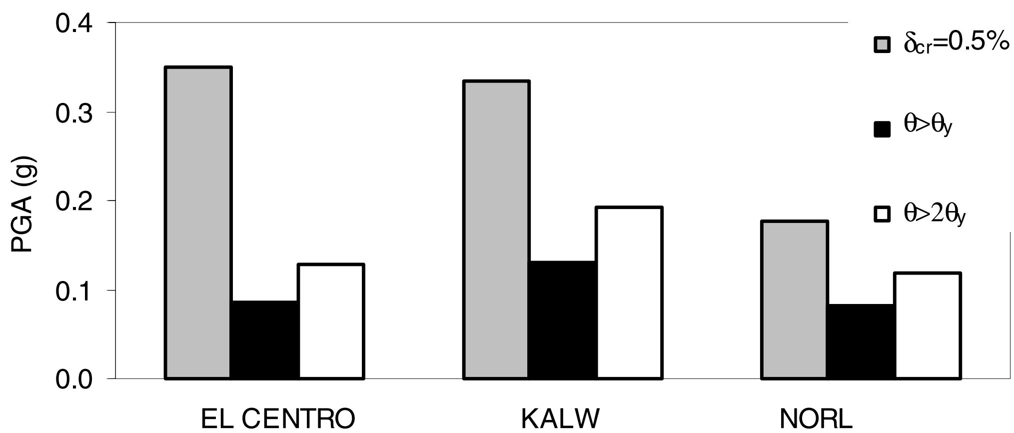

Figure 3. Comparison of peak ground accelerations corresponding to the attainment of the different SLS criteria considered

Repeating a similar exercise as the above, but this time increasing the critical rotation by increments of α=1 where the SLS criterion is defined as $\theta>\alpha\theta_y$, it is found that the scaling factors necessary for exceedance of the 0.5% critical interstory drift are associated with α=5. Therefore, by the time that one of the interstory drifts in the frame reaches 0.5%, in at least one structural element a rotation of five times the yield value is exceeded. In fact, only the beams in the ninth and tenth stories do not form any plastic hinges. Furthermore, yielding already initiates in a few columns, including at least two of the first story columns.

Due to the very low value of critical interstory drift of 0.2% that has been found above to coincide with the first exceedance of a yield rotation anywhere in the frame, a further comparison is attempted. For this purpose, the same frame is subjected to the same three accelerograms, but this time the program RUAUMOKO (Carr, 2001) is employed for the dynamic time-history analysis. Like DRAIN-2000, this program is also based on lumped mass modeling, and exhibits other similar characteristics. However, at

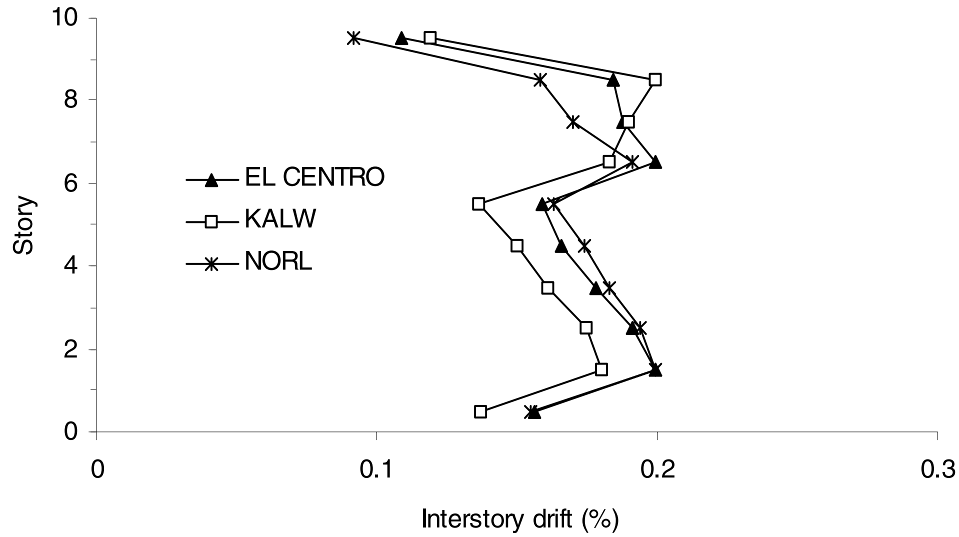

Figure 4. Intestory drift patters when the critical value of 0.2% is first exceeded

Table 3. Safety factors causing attainment of several SLS criteria

	Scaling factors		
SLS criterion	EL CENTRO	KALW	NORL
δ_{cr}=0.5%	1.006	1.225	0.351
$\theta>\theta_y$	0.247	0.480	0.163
$\theta>2\theta_y$	0.370	0.706	0.236
δ_{cr}=0.2%	0.271	0.530	0.164
$\varphi>\varphi_y$ (RUAUMOKO)	0.371	0.251	0.122
δ_{cr}=0.75%	1.569	1.712	0.434

the end of a time-history analysis RUAUMOKO outputs results in terms of curvatures rather than rotations. Therefore, analyses are carried out by altering the scaling factors for the three accelerograms until first exceedance of the yield curvature (or exceedance of unit curvature ductility) is encountered in one of the structural members. The resulting scaling factors are included in Table 3, where it can be clearly seen that these do not coincide with those for $\theta>\theta_y$ that have been obtained previously using DRAIN-2000. Moreover, whereas the first member to yield according to DRAIN-2000 is in most cases encountered on the story of greatest interstory drift, according to RUAUMOKO the first member to yield is always the external, left hand beam on the seventh story. These discrepancies indicate that, for comparisons such as those presented herein, it is preferable to adopt a single software or modeling procedure. Thus, further comparisons involving SLS criteria based on yield curvatures are not attempted.

Finally, for a last comparison, a higher critical interstory drift of 0.75% is investigated. This value is selected as it is the EC8 (CEN, 2003) recommended limiting drift for buildings with ductile nonstructural elements, even though a reduction factor depending on the importance class of the structure may also be applied. Corresponding scaling factors and interstory drift patterns are presented in Table 3 and Figure 5, respectively. As expected, higher scaling factors need to be applied for this criterion to be attained. With the exception of NORL, it is observed that significantly more severe ground motion is needed for an interstory drift of 0.75% rather than 0.5% to be reached. Consequently, a 0.75% drift is also found to be

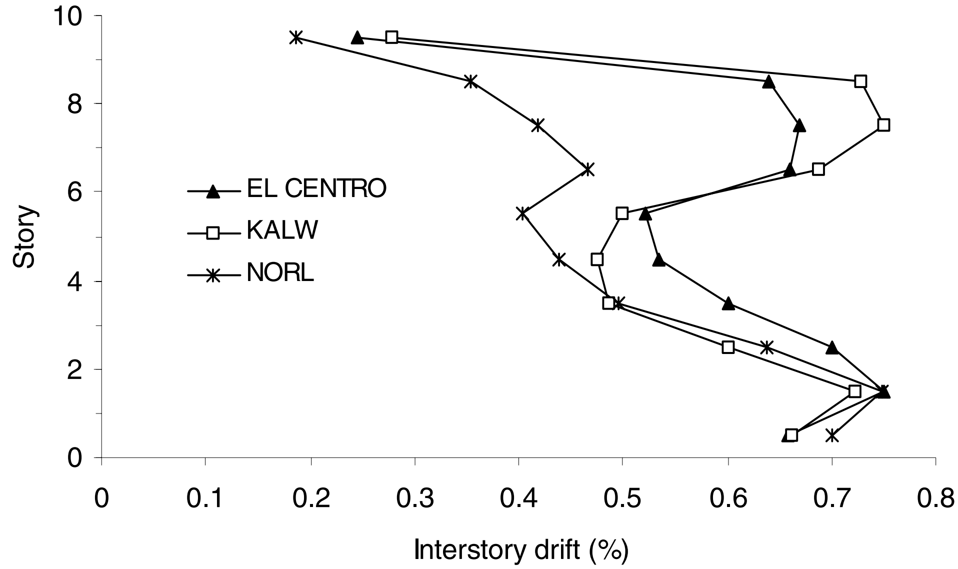

Figure 5. Intestory drift patters when the critical value of 0.75% is first exceeded

accompanied by yielding in most structural elements, including columns. However, as stated earlier, the frame analyzed herein was originally designed to the previous version of EC8 (CEN, 1995) that recommended lower interstory drifts (0.4~0.6%) as SLS criteria.

SUMMARY AND CONCLUSIONS

A brief deterministic study has been presented herein, which successfully illustrated the significance of alternative criteria that can be viewed as acceptable SLS definitions. As pointed out in the state-of-the-art summary that preceded this study, there is a lack of consistency between modern codes of practice as far as the definition of the SLS is concerned. Furthermore, primarily for assessment purposes, researchers tend to choose among a wide variety of possible SLS criteria, depending on the analyzed structural system and on the adopted modeling.

Herein, it has been found that, unless a critical interstory drift as low as 0.2% is selected, higher critical drift values correspond to significant yielding in the structure, which may be interpreted as a damage state beyond serviceability. For serviceability, it is often required that nonstructural elements suffer only a small degree of damage, thus structural elements would in such a case be expected to remain elastic. For a critical drift of 0.5%, which may be viewed as a relatively conservative displacement-based criterion, for all accelerograms considered at least one beam developed a rotation equal to five times the corresponding yield rotation.

The observations presented in this paper are based on analyses carried out on a single structural system using three natural accelerograms. Even though fairly consistent results were obtained from these three accelerograms, a more thorough investigation would be recommended prior to generalizing any conclusions that have been drawn. Such an investigation should of course involve a selection of structures that vary in terms of geometry and structural classification.

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