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MODAL STRAIN-BASED POST-EARTHQUAKE DAMAGE CHARACTERIZATION OF R/C FRAME BUILDINGS

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ABSTRACT

This paper contributes a novel numerical study to assess the potential of the two most widely used modal-strain based damage indices for damage detection in structural components under flexure for post-earthquake damage characterization of reinforced concrete multi-storey planar frame buildings. To this aim, buildings are treated as transversely vibrating beam-like structures and modal strains (i.e., second derivatives of mode shapes) are computed from lateral translational mode shape ordinates known at each floor/slab level along the height of buildings before (healthy state) and after (damaged state) a damaging seismic event. In this setting, the change of modal curvature (MC) along the height of the building as well as the change of modal strain energy (MSE) are adopted as damage sensitive indices and their effectiveness to localize damage to column or to beam elements at different floors and to characterize damage severity is gauged vis-à-vis. This is accomplished by considering computer-generated mode shape data obtained from linear modal analyses applied to finite element models of two different 10-storey r/c planar frames, a single-bay one and a two-bay one, under healthy and several different relatively light damaged states of varying severity. The furnished numerical results demonstrate that both the MC index evaluated based on first mode shape data and the MSE index determined from the first three mode shape data are equally able for both damage localization and severity characterization for most of the damaged case scenarios considered. Further research is warranted to account for the influence of noisy field-recorded mode shape data as well as for sparse instrumentation in which acceleration sensors are not deployed on every building floor.

Keywords: post-earthquake damage detection; mode shapes; modal curvature; modal strain energy; health monitoring

1. INTRODUCTION

Over the past three decades, several damage detection techniques relying on monitoring changes to modal-based damage sensitive indices have been developed and considered in practice to identify long-term ageing and degradation in civil engineering structures and structural components (e.g., Doebling *et al*. 1996, Sohn *et al.* 2002, Humar *et al.* 2006). These techniques are supported by application of operational modal analysis (OMA) or output-only modal analysis (e.g. Brincker and Ventura 2015), to estimate modal properties (i.e., natural frequencies, mode shapes, and damping ratios) of structures in operational conditions. This is commonly achieved by processing acceleration measurements acquired by permanently deployed sensors onto structures linearly vibrating under low-amplitude ambient dynamic loads. In most structures, these loads are due to the action of wind and traffic.

Importantly, in recent years, it has been recognized that the above structural damage detection techniques can facilitate condition assessment of multi-storey building structures instrumented for OMA in the aftermath of major earthquake events (see e.g., Rainieri et al. 2012, Ditommaso et al. 2015 and references therein). This

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consideration can help make timely decisions on post-earthquake structural safety and integrity and, therefore, improve the resiliency of communities against the seismic hazard in earthquake prone areas (e.g., Gatulli et al. 2014). In this context, earthquake-induced damage characterization in buildings has been pursued by adopting modal-based damage sensitive indices in conjunction with structural modal properties estimation undertaken either *during* a seismic event (e.g., Ditomasso et al. 2015, Samimifar and Massumi 2016), or *before and after* the seismic event (e.g. Wang et al. 2007, Liao et al. 2008, Hsu and Loh 2008, Gkoktsi et al. 2017). The former monitoring strategy involves the consideration of nonlinear system identification techniques based on non-stationary response acceleration signal processing to trace time-varying structural modal properties during strong ground motion excitation. The latter monitoring strategy is algorithmically simpler to implement as it involves the application of standard OMA (i.e., stationary excitation and linear structural response assumptions apply) to estimate mode shapes before (healthy state) and after (potentially damaged state) the strong ground motion. In this regard, it is applicable so long that environmental conditions known to affect modal properties, such as temperature and humidity, remain the same before and after the seismic event: a reasonable assumption to make given the short duration of earthquakes.

In this setting, Hsu and Loh (2008) considered the modal strain energy (MSE) damage index, originally proposed by Stubbs et al. (1992), to localize damage at the base of the ground floor columns of a full-scale single-bay three-storey steel frame building based on modal properties of the healthy (pre-earthquake) and of the damaged (post-earthquake) state. Structural damage was introduced by locally slicing the flanges of the steel column sections to model the effect of a virtual plastic hinge. Moreover, Liao et al. (2008) compared the potential of five alternative modal-based damage sensitive indices excluding the MSE, to characterize earthquake-induced damage to a scaled-down specimen of a 38-storey reinforced concrete (r/c) building subject to seismic excitation through a shaking table. Five different intensity levels of seismic excitation were considered spanning light to near collapse limit state while OMA using low-intensity broadband seismic excitation at the end of each seismic excitation was conducted. It was found that the story damage index (SDI), proposed by Wang et al. (2007), performed better in resolving the mostly damaged stories for each seismic excitation level as identified through visual inspection of the specimen. More recently, Ditomasso et al. (2015) adopted the modal curvature (MC) index, firstly introduced by Pandey et al. (1991) for damage localization purposes, to characterize the evolution of earthquake induced damage in yielding building structures during strong ground motion. The authors addressed the time-varying aspect of the problem by employing the S-transform for joint time-frequency analysis of response acceleration signals. Promising results on the capability of MC to localise earthquake induced damage in framed multi-storey r/c building were reported based on both numerical data obtained through nonlinear response history analysis and on experimental shaking table tests data involving a scaled-down concrete frame.

The above literature survey suggests that, although the MC and MSE damage indices have been successfully considered for earthquake induced damage identification in multi-storey buildings, no systematic comparative study has been undertaken to assess vis-à-vis their potential for damage localization and severity characterization relying on modal properties before and after a seismic event. To this end, this paper undertakes a comprehensive numerical investigation to resolve single and multiple plastic-hinge-like damage localized at critical cross-sections in beams and columns of typical code-compliant r/c moment resisting frames with varying severity using the MC and MSE indices. A main reason for examining exclusively these indices is that, unlike the SDI (Wang et al. 2007) as well as other bona fide damage indices (e.g., Humar et al. 2006), the computation of MC and MSE does not require any knowledge or assumption of mass distribution along the building height which may not be readily available before and/or after a seismic event. Further, they are both based on modal strains (i.e., second derivative of mode shapes) whose sensitivity and damage localization efficacy is well-established for health monitoring of continuous structural members such as beams and plates (Li 2010). In this respect, frame buildings are herein treated as beam-like transversely vibrating structures along their height with global lateral modes of vibration acquired through standard linear (operational) modal analysis.

The remainder of this paper is organized as follows. Section 2 reviews briefly the mathematical background of the MC and the MSE damage indices for damage detection. Section 3 discusses the adopted methodology for assessing the above indices for post-earthquake damage detection in framed building structures and describes the finite element (FE) modeling of benchmark structures in healthy and damaged states. Section 4 presents and discusses pertinent numerical results probing into the potential of the MC and the MSE indices to localize damage and to characterize its severity for different damage scenarios. Lastly, Section 5 summarizes concluding remarks.

2. REVIEW OF MODAL STRAIN-BASED DAMAGE DETECTION METHODS

2.1 Modal curvature (MC) method for damage detection in beam-like structures

Damage in flexural types of structures is typically associated with (local) changes to their flexural rigidity which result in variations to their vibration modes obtained from OMA. Nevertheless, such variations are not readily detectable for well-localized damage, especially when considering low-frequency vibration modes. Note that commonly only low-frequency modes are identified from field measurements in the context of OMA since higher-modes are usually not sufficiently excited by ambient broadband dynamic loads while a meaningful estimation may require impractically dense instrumentation. To this end, comparing *derivatives* of low-frequency vibration modes extracted from healthy and damaged states facilitates significantly damage identification and localization. This is because, from a signal processing perspective, differentiation magnifies local high-frequency trends indicative of any potential local damage while smoothens out low-frequencies that do not normally carry any damage-related information (Worden 1990). In this respect, Pandey et al. (1991) proposed tracking differences of the second derivative of any single flexural vibration mode, i.e., modal curvature (MC) or strain, between two states to infer damage. Conveniently, the use of MC as a damage index in beam-like structures is justified by the fact that the curvature (second derivative of deflected shape) is inversely proportional to the flexural stiffness and tends to increase when the cross-sectional moment of inertia reduces due to damage.

For practical implementation, let $\psi_i(x_k)$ and $\psi_i^d(x_k)$ be the *i*-th vibration mode of the healthy and of the damaged state, respectively, of a beam-like structure at ordinate *k*. The ordinate *n* for which the change (difference) in mode shape curvature expressed as

$$\Delta\psi_i''(x_n) = \left|\psi_i''^d(x_n) - \psi_i''(x_n)\right| \tag{1}$$

attains a (*local*) *maximum* corresponds to a potential damage location. In the above equation and henceforth a prime over a symbol denotes differentiation with respect to the *x* (space) variable. Assuming a beam-like structure with mode shape ψ_i measured at *K* points/ordinates x_k, *k*= 0,1,2,…,*K*-1 equally-spaced by *h*, the modal curvatures (or strains) in Equation (1) can be estimated by using the central difference formula

$$\psi_i''(x_k) = \frac{\psi_i(x_{k+1}) - 2\psi_i(x_k) + \psi_i(x_{k-1})}{h^2}. \tag{2}$$

2.2 Modal strain energy (MSE) method for damage detection in beam-like structures

The MSE damage index, firstly proposed by Stubbs et al. (1992), is arguably the most widely considered for modal-strain based damage detection applicable to any multi-member pinned or rigid jointed skeletal structure (see e.g., Humar et al. 2006, Hsu and Loh 2008 and references therein). The herein considered version of the MSE method relies on monitoring changes to the strain energy stored in flexural Euler-Bernoulli beam-type members of a healthy and of damaged structure oscillating under one or more vibration modes simultaneously. Specifically, consider a beam-like structure of total length *L* with continuously distributed flexural rigidity *EI*(*x*). The modal strain energy stored in the healthy state of the structure due to oscillation according to the *i*-th mode is

$$S_i = \int_0^L EI(x)[\psi_i''(x)]^2 dx. \tag{1}$$

Let the structure be divided into *j*=1,2,…,*J* elements. The modal strain energy contributed by the *j*-th element with length extending between *x*=*a* and *x*=*b* ordinates and having a constant flexural rigidity EI_j is given by

$$S_{ij} = \int_a^b EI_j [\psi_i''(x)]^2 dx. \tag{2}$$

In this setting, the ratio $F_{ij} = S_{ij}/S_i$ gives the fraction of the total strain energy in the healthy structure contributed by element *j*. Accordingly, the total strain energy stored in the damaged state of the same structure for the *i*-th mode is given as

$$S_i^d = \int_0^L EI^d(x) [\psi_i^{d''}]^2 dx, \tag{3}$$

where $EI^d(x)$ is the flexural rigidity of the damaged structure, while the modal strain energy contributed by the j^{th} element reads as

$$S_{ij}^d = \int_a^b EI_j^d [\psi_i^{d''}]^2 dx, \tag{4}$$

where EI_j^d is the constant rigidity of the *j*-th member. Further, fraction of the total strain energy in the damaged structure contributed by element j is defined as $F_{ij}^d = S_{ij}^d / S_i^d$. Under the assumption that the damage is well localized and affects only a small number of the J elements, $EI^d(x)$ in Equation (5) can be approximated by $EI(x)$. This assumption offers the opportunity to define the following MSE-based damage index for the *j*-th element in the *i*-th vibration mode (e.g., Humar et al. 2006)

$$\gamma_{ij} = \frac{EI_j}{EI_j^d} = f_{ij}^d \times f_{ij}, \tag{7}$$

where

$$f_{ij} = \frac{\int_a^b [\psi_i''(x)]^2 dx}{\int_0^L EI(x) [\psi_i''(x)]^2 dx} \quad \text{and} \quad f_{ij}^d = \frac{\int_a^b [\psi_i^{d''}(x)]^2 dx}{\int_0^L EI(x) [\psi_i^{''}(x)]^2 dx}. \tag{8}$$

Clearly, if $\gamma_{ij} > 1$ a reduction of the flexural rigidity within the *j*-th element has occurred indicative of a local damage between $x=a$ and $x=b$ ordinates. From a practical viewpoint, it is important to note that only the flexural rigidity of the healthy structure enters the calculation of the damage index in Equation (7), which in the case r/c structures requires the sole knowledge of the outer dimensions of concrete members as well as the material modulus of elasticity. Lastly, if M modes of vibration are measured, they can all be simultaneously used for damage detection by means of the following generalization of the MSE damage index

$$\gamma_j = \frac{\sum_{i=1}^M f_{ij}^d}{\sum_{i=1}^M f_{ij}}. \tag{5}$$

3. METHODOLOGY FOR POST-EARTHQUAKE MODAL-STRAIN BASED DAMAGE DETECTION IN PLANAR R/C FRAMES AND STRUCTURAL MODELLING

In applying the indices defined in Equations (1) and (9) for post-earthquake damage detection of planar r/c multi-storey frame buildings, it is herein proposed to treat such buildings as beam-like structures represented in the modal domain by their global lateral modes of vibration. In practice, such modes are estimated through OMA using horizontal floor accelerations measurements at a sufficient number of floors. For earthquake-induced damage detection, mode shapes before and shortly after a major seismic event are used corresponding to the healthy and damaged structure, respectively. It is assumed that environmental conditions affecting mode shapes remain the same before and after the earthquake and thus changes to the damage indices along the height of the building can be interpreted as evidence of local stiffness reduction due to earthquake-induced plastic hinge formation at critical cross-sections of structural members. This interpretation is motivated by the well-established practice of representing structural systems exhibiting nonlinear material behaviour under seismic excitation using equivalent linear systems of reduced stiffness compared to the pre-yielding stiffness of the non-linear system (see e.g., Giaralis and Spanos 2010, Günay and Sucuoğlu 2010, Mitseas et al. 2018 and references therein).

In this work, the potential of the above strategy for modal-strain based post-earthquake damage detection is numerically investigated using computer-generated mode shape data pertaining to the two 10-storey frame buildings whose geometry and cross-sectional properties are shown in Figure 1. This approach enables the consideration of a large number of well-defined damage states to gauge the sensitivity of the adopted indices and the validity of the damage detection strategy to localize damage at different members and critical cross-sections and to discriminate its severity level. The frames are modelled in SAP2000 commercial software using standard linear Euler-Bernoulli beam elements. The nominal concrete strength is taken as 20MPa having modulus of elasticity equal to $3x10^7$ kN/m^2. Mass is lumped at each floor level and is taken equal to 36tons per story and per bay for all floors except for the last floor which is halved.

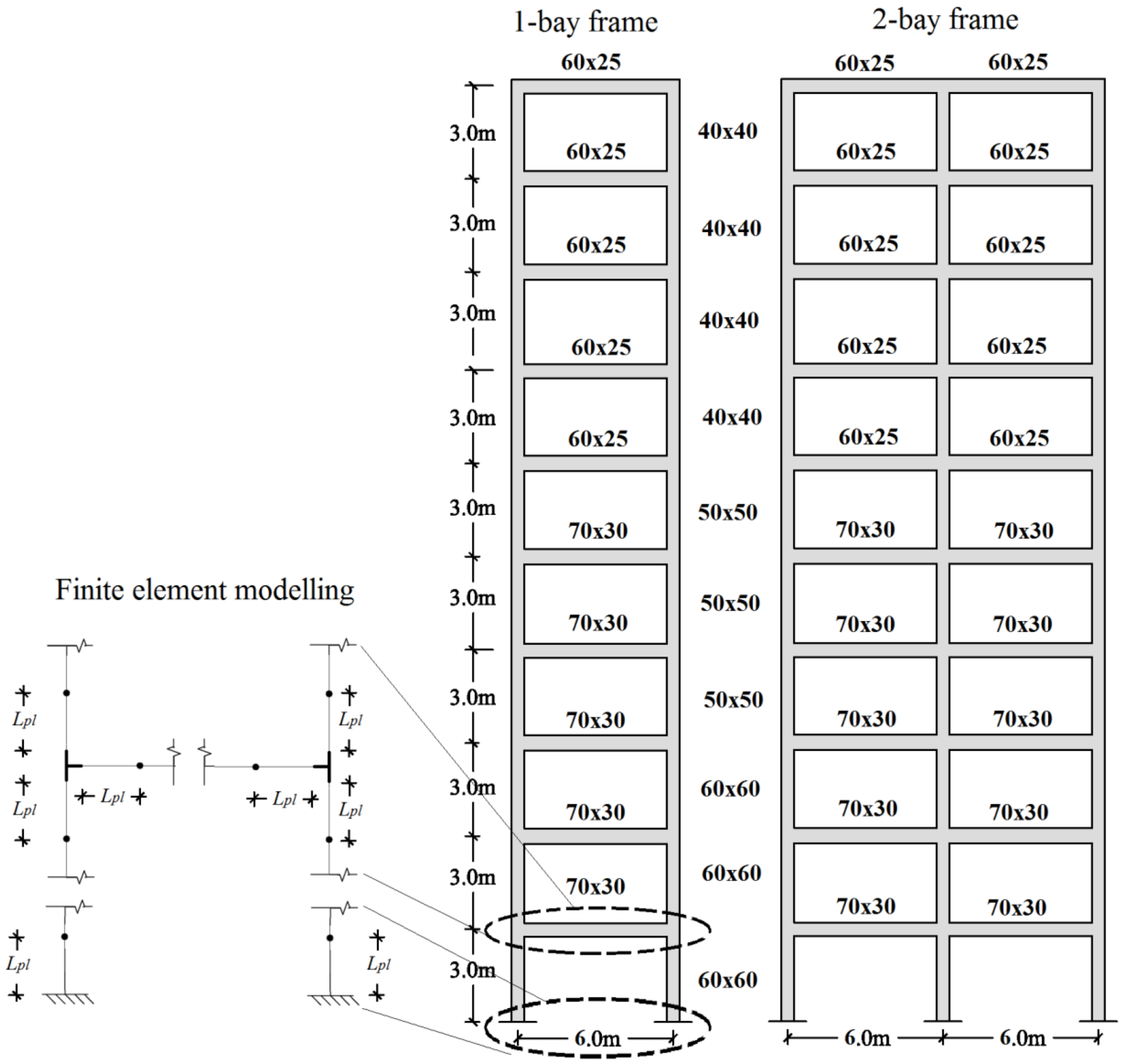

Figure 1: Considered planar r/c frame structures and finite element modelling of earthquake-induced damage

A large number of different damaged states (location and severity) of the frames in Figure 1 are examined in the next section modelled by local flexural rigidity reduction at the ends of various beam and column members within a plastic hinge length, L_{pl} (see also Günay and Sucuoğlu 2010, Gkoktsi et al. 2017). This is achieved in FE modelling by considering Euler-Bernoulli elements of length L_{pl} which, depending on the damaged scenario examined, are assigned a reduced flexural stiffness compared to the healthy member. In doing so, rigid offsets corresponding to the geometry of joints are also accounted for. The adopted FE modelling approach for damaged states is pictorially illustrated in Figure 1 for the base of columns and for two typical joints. The length L_{pl} for each member is found by the empirical formula (Priestley et al. 2007)

$$L_{pl} = max\left\{min\left(0.2\left(\frac{f_{uk}}{f_{yk}} - 1\right)L_o, 0.08\right) + 0.022 f_{yk} d_{bl}\ ,\ 0.044 f_{yk} d_{bl}\right\}, \tag{10}$$

where L_o is the shear span taken as half of the length of structural members, d_{bl} is the diameter of the longitudinal reinforcement taken equal to 20mm, f_{yk} is the characteristic steel yielding strength taken equal to 400MPa and f_{uk}/f_{yk} is the steel hardening ratio taken equal to 1.15.

4. NUMERICAL RESULTS AND DISCUSSION

This section presents and discusses numerical results illustrating the applicability of the proposed modal strain-based approach for post-earthquake damage detection detailed in Section 3 and the sensitivity of the MC and MSE damage indices for the purpose in Equations (1) and (9). In particular, 11 different damage scenarios are considered assuming plastic hinge formation at different ends of beam and column members in the frame buildings of Figure 1. For each damage scenario, three different levels of damage severity is modelled by reducing flexural rigidity within the damaged L_{pl} –long elements by 10%, 20%, and 30% compared to the healthy state. Note that these flexural rigidity reductions correspond to relatively light damage which may not be readily detectable through visual inspection while they impart negligible changes to the structural natural frequencies (see also Günay and Sucuoğlu 2010 and Gkoktsi et al. 2017). Standard linear modal analysis in SAP2000 software is conducted to retrieve the three first mode shapes of the healthy and of all damaged states. Note that the assumption of lumping the total mass of structures at floor levels in FE modelling results in retrieving global lateral mode shape ordinates at each floor level. These computer-generated data correspond to modes that would have been extracted in an OMA deployment if sensors measuring lateral floor accelerations are placed on each floor of the frame structures and sufficiently strong ambient noise exists to excite the first three translational lateral modes.

To facilitate an interpretation of numerical results, the MC and MSE damage indices computed from Equations (1) and (9), respectively, using the above computer-generated mode shape data are plotted vis-à-vis for each of the 11 damage scenarios and for all damage severities in the following 11 figures of the paper. In the leftmost panel (a) in each of these figures, the examined damage scenario is pictorially defined by indicating the plastic hinge location within the considered structure. The central two panels of the figures plot the change of mode curvature normalized to the peak value from all curves along the building height for the lightest damage severity (10% reduction) using only the 1st, 2nd, and 3rd mode shape, panels (b), and for the three levels of damage severity using the 1st mode shape. Lastly, the rightmost panel (d) plots the MSE damage index of Equation (9) for all three damage severity levels using the three first mode shapes, i.e., M=3. The central difference formula in Equation (2) is used to computed the required second derivatives of mode shapes using K=10 mode shape ordinates at each floor height of the building (the ordinate at the base of the columns is trivially set equal to zero). Further, the flexural rigidity of only the columns is considered in computing $EI(x)$ in Equation (8) in between different floors. The presentation begins with discussing damage scenarios at column members for the single bay frame in Figure 1.

4.1 Column damage scenarios for single bay frame

Figure 2 considers the case of a single damaged ground floor column. Figures 2(b) and 2(c) demonstrate that changes of 1st mode modal curvature achieves accurate damage localization and severity characterization manifested by a single prominent peak in the graphs at the ground level which is higher as damage severity (i.e., increasing stiffness reduction at the ground floor column plastic hinge) increases. Looking at changes to the curvature of higher modes, local maxima are observed, especially for the 3rd mode, at higher floors where there is no damage which indicates that for this particular case modal strains of higher modes are overly sensitive and should not be used. Lastly, Figure 4(d) suggests that the MSE can also accurately resolve the damage at the ground floor since it attains a positive peak value at floor height zero. This value increases for increasing damage severity.

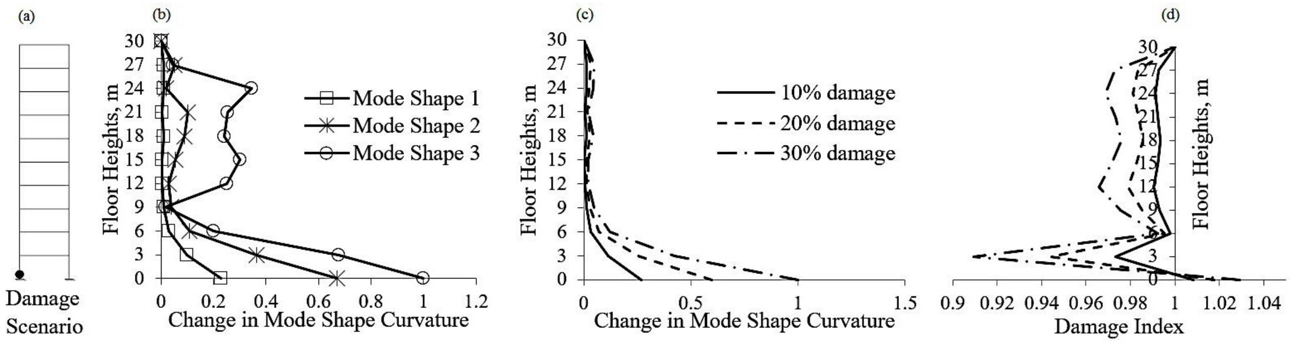

Figure 2: Damage scenario 1- Ground floor column damage

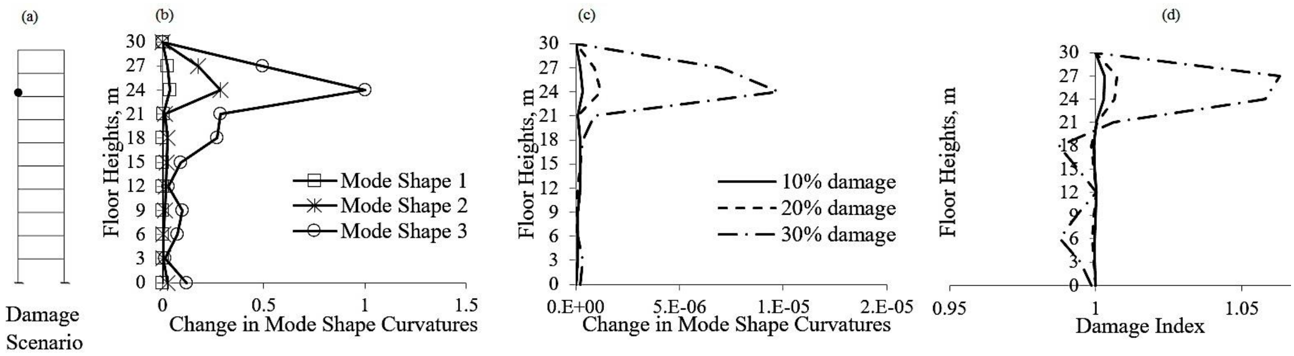

Figure 3: Damage scenario 2- 8^{th} floor column damage

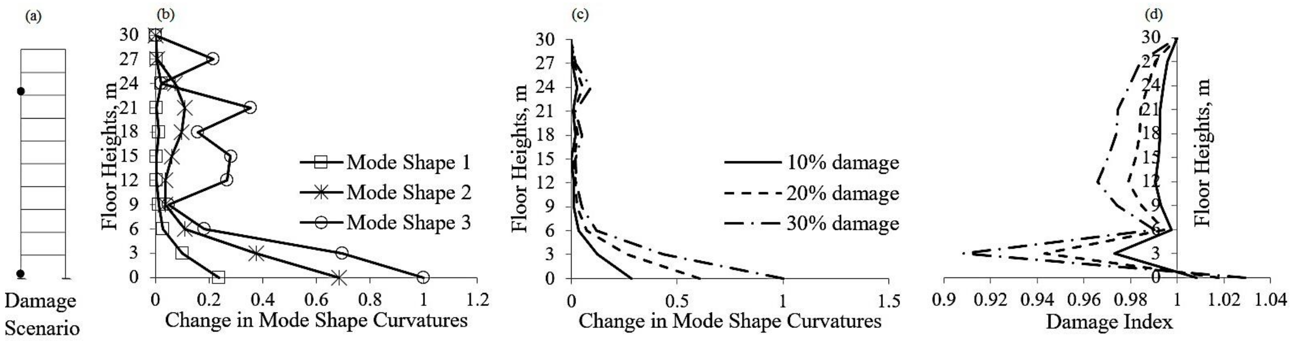

Figure 4: Damage scenario 3- Simultaneous ground and 8^{th} floor column damage

The exact same conclusions are drawn for the case of a damaged column located at the 8^{th} floor examined in Figure 3: changes to 1^{st} mode curvature as well as the MSE index are quite capable of resolving the damaged floor even for the very light damage case of 10% stiffness reduction. Nevertheless, this is not the case for the, more challenging, damage scenario of Figure 4 considering simultaneous damage at a ground and at a 8^{th} floor column. The MSE index can only locate the damage at the ground floor, while the 1^{st} mode MC index resolves both damages only for the largest damage severity of 30% stiffness reduction. One observes from Figure 4(b) that the 2^{nd} mode MC index is most potent to resolve damages at both ground and 8^{th} floor, however, a comparison with the damage scenario of Figure 2 suggests that this is only coincidental. Overall, it is concluded that 1^{st} mode MC and MSE indices can readily resolve damages at a single floor, while only the 1^{st} mode MC index resolves damages at two floors simultaneously and only for sufficiently severe damages. It is further seen that damage indices are better off to resolve damages at the ground floor columns than at higher floors.

4.2 Column damage scenarios for two bay frame

Figures 5 and 6 consider the same damage scenarios as Figures 2 and 4, but for the two bay frame of Figure 1 introducing damage to the internal column. Looking at Figure 5 first, the exact same conclusions are drawn as from Figure 2. More importantly, results of Figures 2 and 5 suggest that the proposed approach of treating multi-storey frames as transversely vibrating beam-like structures with modal ordinates computed/measured at floor levels is applicable and provides meaningful outcomes irrespective of the number of frame bays. Turning the attention to Figure 6, it is seen that for the two-bay frame, damage at the 8th floor is resolved at the same ease as damage to the ground floor by the 1st mode MC index, while MC index from higher modes is (once again) overly sensitive exhibiting spurious local peaks at floors free of damage. Further, the MSE index is able to resolve simultaneous damage to the ground and to the 8th floor with some accuracy.

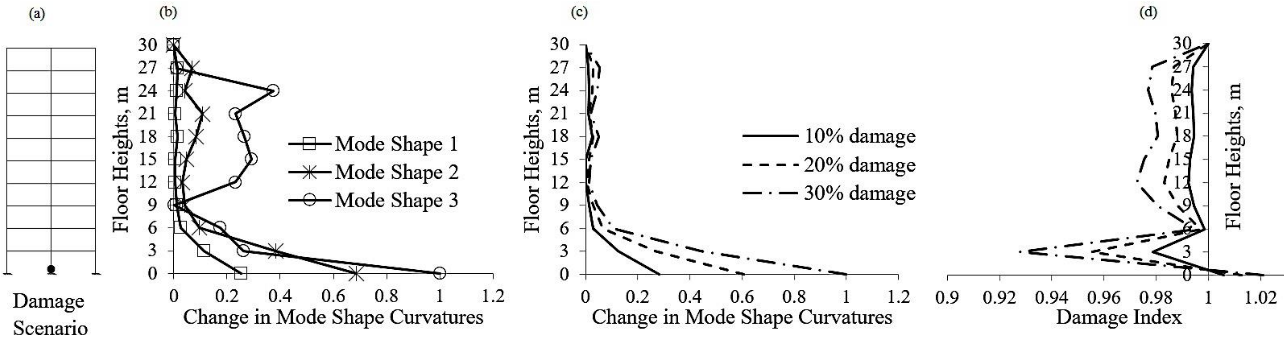

Figure 5: Damage scenario 4- Ground floor internal column damage

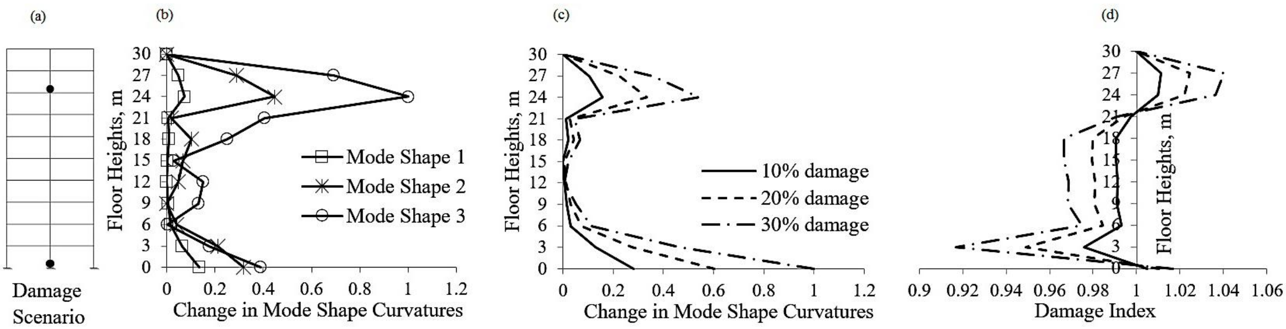

Figure 6: Damage scenario 5- Simultaneous ground and 8th lower internal column damages

4.3 Beam damage scenarios

This sub-section examines damage detection performance for scenarios where plastic hinge-like damage occurs at various beams of the one-bay frame of Figure 1. Figures 7 and 8 consider damage at both ends and at only one end, respectively, of the ground story beam. Evidently, both the 1st mode MC index and the MSE index are able to clearly resolve these two damage scenarios, both in terms of location and in terms of severity. This is manifested by developing two prominent local peaks one floor/slab level above (second floor at 6m height) and one below (ground slab at 0m height) the floor/slab level of the damaged beam (first floor at 3m height). These peaks become larger for increasing loss of stiffness level. They are also higher for the case of two damaged beam ends vis-à-vis a single damaged beam end: this is only observable by comparing the rightmost panels of Figures 7 and 8 plotting the MSE indices as the normalization used in plotting the MC indices does not facilitate a comparison across different damage scenarios. However, it is herein reported that this is the case for the MC indices as well. Lastly, it is again observed that MC indices based on higher modes are not useful for damage detection due to excessive sensitivity to changes.

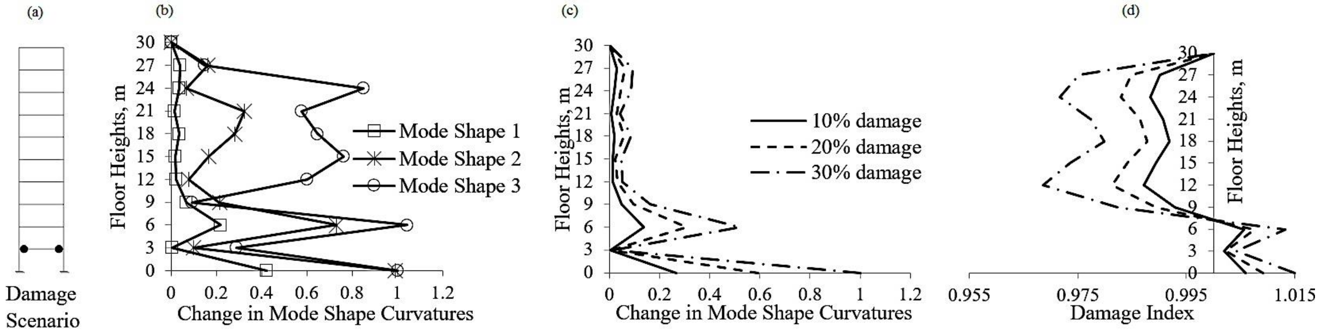

Figure 7: Damage scenario 6- 1st floor beam damage at both ends

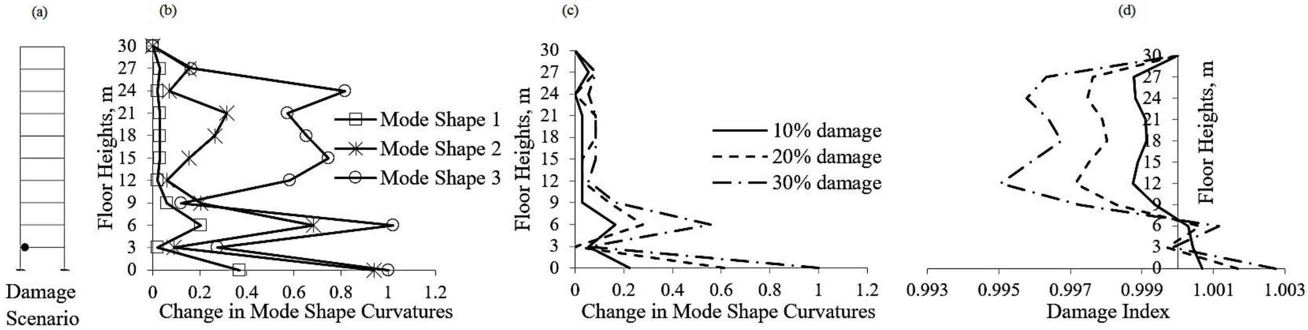

Figure 8: Damage scenario 7- 1st floor beam damage at one end

Note that the above described beam damage detection pattern in the indices is very different from the pattern associated with damages at the ends of columns (see figures 2 to 6) deduced by a single peak at the closest to the damage slab level. The beam damage detection pattern observed by the herein proposed approach is justified by considering that loss of stiffness at a beam of the *k*-th floor in a multi-storey frame will not affect the lateral mode shape ordinate of the k-th floor, but it will affect the mode shape ordinates at the neighbouring floors (*k*-1)-th and/or (*k*+1)-th. This consideration and the associated damage detection pattern in Figures 7 and 8 (as well as in Figures 9 to 12 discussed further below) demonstrates the usefulness and applicability of the proposed post-earthquake damage detection approach for discriminating damage related to plastic hinge formation at beams as opposed to plastic hinge formation at columns.

Next, Figures 9 and 10 consider damage at both ends and at only one end, respectively, of the 8th story beam. The same conclusions are drawn as for the case of the ground story beam damage with regards to the potential of the 1st mode MC and the SME indices for damage localization and severity characterization. It is however interesting to note that the SME index does not exhibit a prominent peak at the 7th floor (at 21m height), a fact that can be attributed to the change of the columns cross-section at the 6th floor which makes the index value to be constant (flat) and positive at heights 18m and 21m.

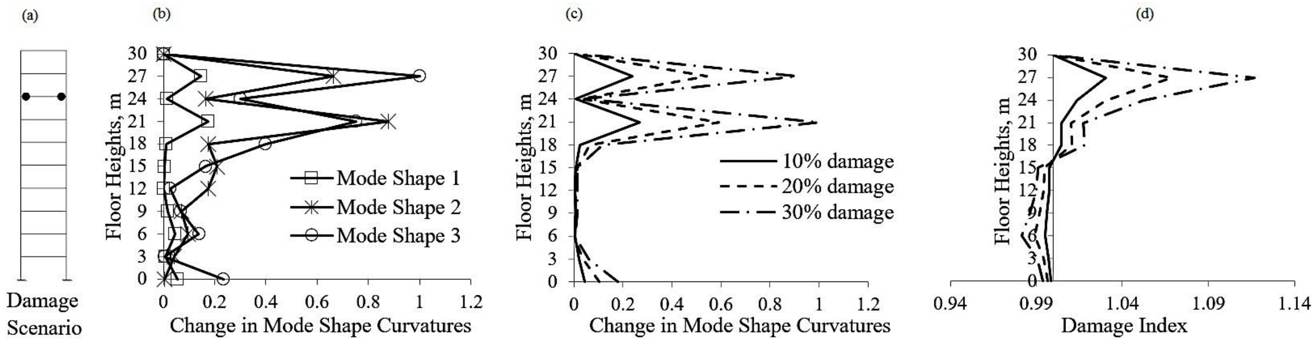

Figure 9: Damage scenario 8- 8th floor beam damage at both ends

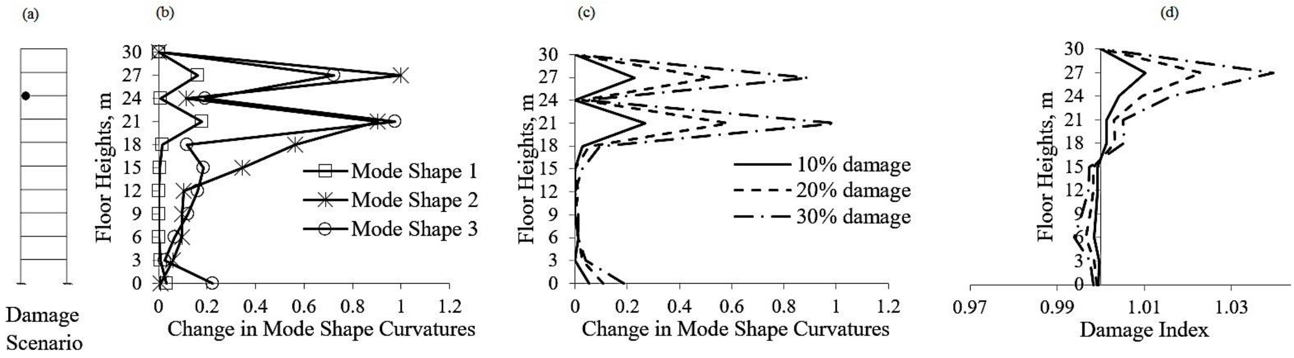

Figure 10: Damage scenario 9- 8th floor beam damage at one end

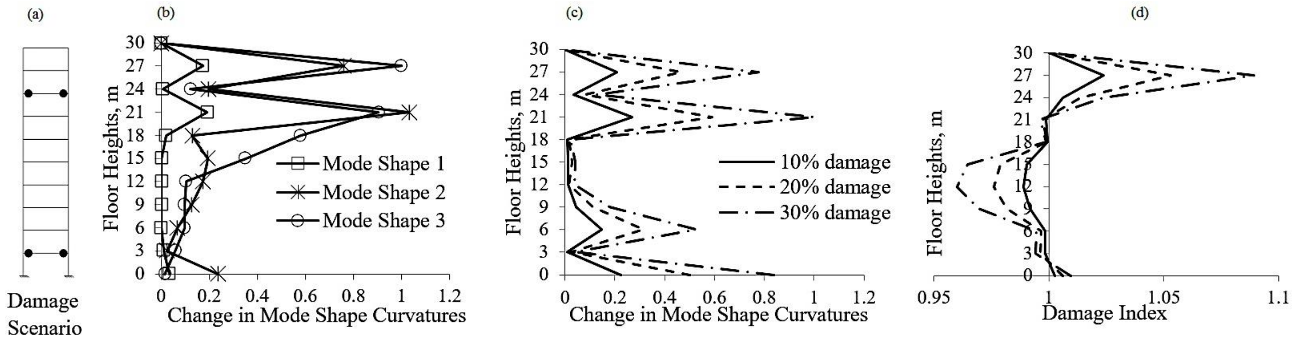

Figure 11: Damage scenario 10- Simultaneous 1st floor and 8th floor beam damage at both ends

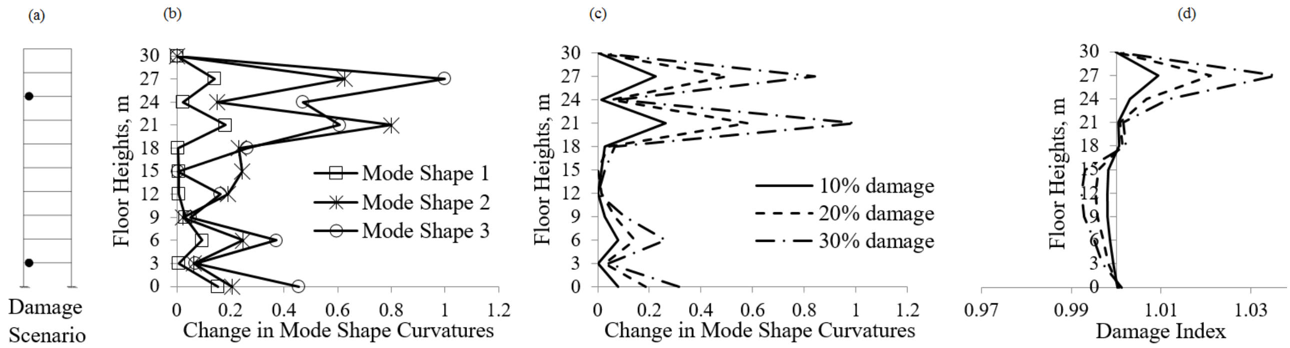

Figure 12: Damage scenario 11- Simultaneous 1st floor and 8th floor beam damage at one end

Lastly, Figures 11 and 12 combines the damage scenarios examined in Figures 7 and 9, and 8 and 10, respectively, that is, simultaneous beam damage at the ground and at the 8th story at both beam ends and at one beam end, respectively. The 1st mode MC index is quite capable to localize and to characterize the damage severity in both the combined damage scenarios exhibiting the double local peak damage identification beam pattern. The MSE resolves clearly only the 8th floor damage. The ground floor damage is only resolved when both the ends of the ground floor beam develop plastic hinges.

5. CONCLUDING REMARKS

The potential and applicability of the two most widely used modal-strain based damage indices for damage detection in structural components under flexure, namely the MC and the MSE, have been assessed for post-earthquake damage characterization of r/c multi-storey planar frame buildings. This has been enabled by treating buildings as transversely vibrating beam-like structures and by focusing on modal curvatures (second derivatives of mode shapes) extracted from lateral global mode shape ordinates known at each floor/slab level along the height of buildings before (healthy state) and after (damaged state) a damaging seismic event. It has been argued that such modal ordinates can be readily obtained in the field by application of operational modal analysis to floor lateral translational acceleration time-histories measured by sensors deployed on each building floor.

For numerical assessment, computer-generated mode shape data have been herein considered obtained from linear modal analyses applied to FE models of two different 10-storey r/c planar frames, a single-bay one and a two-bay one, under healthy and several different damaged states corresponding to relatively light damage, i.e., most probably not visible through standard visual inspection. Earthquake-induced damage has been introduced to the FE models through varying local flexural rigidity reduction within the critical zones of beam and column members. The furnished numerical results have demonstrated the validity of interpreting framed buildings as beam-like structures as well as the potential of the MC and MSE damage indices to (i) localize damage at a column or at a beam at a single or at two different floors, and (ii) discriminate the severity of damage leveraged by the percentage reduction of flexural rigidity. Particularly, it was found that the MC index estimated by first mode shape ordinates is rather efficient for accurate damage localization and severity discrimination, while MC index computed from higher modes is overly sensitive for the purpose. Further, the MSE index as determined from the first three mode shape coordinates was found to be equally powerful with first mode MC index for post-earthquake damage characterization.

Further research is on-going by the authors to address the case of more sparse instrumentation than the one assumed in the herein reported results, as well as to gauge the influence of infill walls and the effectiveness of the considered modal-strain based indices for post-earthquake damage detection for field-recorded noisy modes.

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