A NEW STRAIN-BASED MEMBER DAMAGE CLASSIFICATION FOR POST-EARTHQUAKE VISUAL ASSESSMENT OF RC FRAME BUILDINGS

S. Shiradhonkar(1), R. Sinha(2)

(1) *Assistant professor, Indian Institute of Technology Roorkee, India, saurabhrsfeq@iitr.ac.in*
(2) *Professor, Indian Institute of Technology Bombay, India, rsinha@civil.iitb.ac.in*

Abstract

The critical task after the major earthquake is to inspect all the buildings in the affected areas and classify them into a safe and unsafe category. Identification of unsafe buildings is essential to avoid loss of life during aftershocks, while identification of safe albeit damaged buildings is important to minimize business interruption losses and to reduce need for avoidable temporary shelters. Thus, the classification of extent of damage to buildings during earthquake excitation is an important issue for the earthquake engineering community. Visual damage state definitions, providing a clear description of damage characteristics and failure mechanisms, are used to classify building damage into different damage levels. Several damage state definitions are proposed in the literature to classify seismic damage in reinforced concrete buildings using visual parameters. The existing visual damage state classifications were mainly developed based on observed damage during past earthquakes and using experts' opinion. As a result, the existing visual damage states are not explicitly correlated with engineering response parameters. Consequently, the damage is not classified on the basis of loss in the lateral load-carrying capacity of damaged members and that of the entire building. In the absence of such correlation, the damaged building is generally assessed conservatively during visual survey. A conservative engineering assessment of damaged building extracts a heavy toll due to loss of operation of safe but inaccurately tagged damaged buildings. Conversely, unconservative errors, that categorize an unsafe building as safe, expose their occupants to grave risks during aftershocks. Thus, accurate visual damage assessment methods are required for efficient decision making during the post-earthquake situation.

In the present paper, the relationship between visual damage definition and the response parameters is proposed such that it relates damage in individual members with the loss in building's lateral resistance. Damage to reinforced concrete members is comprehensively addressed in the present study. Critical levels of damage in RC members are defined on the basis failure mechanics of reinforced concrete section. The critical damage states are correlated with strain limits and residual crack widths using simulation of published experimental results. Data of experimentally-observed responses from Pacific Earthquake Engineering Research (PEER) Centre experimental database are simulated analytically using IDARC-2D. The simulations are used to develop fragility functions of critical member damage states in terms of extreme fiber compressive strain and residual crack width. The limiting values of extreme fiber compressive strain and measurable residual crack width at critical damage states are established using developed fragility curves. A new member visual damage state definition addressing a wide range of moderate damage is proposed in terms of extreme fiber compressive strain and residual crack width limits. From the investigation, it is also observed that the curvature ductility (engineering response parameter) at intermediate member damage states is not dependent on the ultimate deformation characteristics of the member. Thus, the proposed visual member damage state definition is useful to classify damage in the RC buildings, which have been designed and constructed by different design codes and at different periods of time.

Keywords: Post-earthquake damage assessment, visual member damage states, strain-based member damage classification

1. Introduction

Classification of the extent of damage of reinforced concrete buildings during earthquake excitation is an important issue for the earthquake engineering community. The classification of damage is necessary to conclude on the residual lateral capacity of the damaged building in the post-earthquake situation. Visual damage assessment methods, which can be rapidly applied to a large number of buildings, are commonly used by emergency managers for damage assessment during the post-earthquake situation. These methods have traditionally focused on qualitative criteria to characterize the size of earthquakes in terms of intensity measures such as EMS-98 [1]. ATC-13 [2] subdivided MMI damage scale into repairable and non-repairable damage categories for 78 types of representative California buildings. The ATC-13 definition provides a basis for post-earthquake safety evaluation measures in ATC-20 [3]. Goretti and DiPasquale [4] reviewed post-earthquake survey methods and classified them based on their objective and time interval after the earthquake when the survey was conducted.

Under earthquake ground motion, maximum strain occurs on tension face of the member for the flexural dominant response of the members. Crack size and number of cracks both are related to the stress in the extreme fiber. Flexural strain provides a consistent basis to establish the relationship between seismic demand and member capacity. Thus, visual parameters related to flexural strain such as crack width are useful measures to interpret the force experienced by the member during the post-earthquake situation.

Table 1 – Damage classification and corresponding crack width limits for structural members as per available methods

Damage description	Crack widths and damage states		
	Ohkubo (1991)	**Sinha and Goyal (2004)**	**Anagnostopoulos and Moretti (2008)**
Narrow cracks on surface of concrete	Rank I - crack width less than 0.2 mm	State 1 - crack width less than 0.1 mm	I – None - crack width less than 0.5 mm
Visible but narrow cracks on surface of concrete	Rank II - crack width 0.2 to 1.0 mm	State 2 - crack width 0.1 to 0.2 mm	II – Slight - crack width 0.5 to 2.0 mm
Local crush of covered concrete considerably big cracks	Rank III - crack width 1.0 to 2.0 mm	State 3 - crack width 0.2 to 0.5 mm	III - Moderate – Heavy - crack width 2.0 to 5.0 mm
Remarkable crush of concrete with exposed rebars, cover spalled off	Rank IV - crack width greater than 2 mm	State 4 - crack width 0.5 to 3.0 mm	IV – Severe – crack - width greater than 5 mm
Rebars bent, core concrete crushed visible deformation of column	Rank V	State 5- crack width greater than 3 mm	

Ohkubo [5] introduced damage rank for post-earthquake visual damage assessment of buildings in terms of observed crack widths in individual structural members. Similarly, Sinha and Goyal [6] proposed crack width-based damage state definitions based on observations after Killari (in 1993), Jabalpur (in 1999) and Bhuj earthquakes (in 2001) in India. Anagnostopoulos and Moretti [7], Tu et al. [8] and Taskin et al. [9] used data from past earthquakes and expert opinion to develop crack width-based post-earthquake damage assessment procedures for Greece, Taiwan, and Turkey, respectively. The summary of the above crack width-based member damage state definitions is presented in Table 1. It can be observed that crack width limits proposed by different researchers differ significantly for similar damage description.

The existing damage definitions have been developed based on the damage observations during past earthquakes and as a result, they do not explicitly correlate visual observations with engineering response parameters and loss in the capacity of the member. A conservative engineering assessment of building status extracts a heavy toll due to loss of operation of safe but inaccurately tagged buildings. While the unconservative errors, by categorizing unsafe building as safe, expose the occupants to grave risks during aftershocks. The accuracy of visual assessment methods can be improved by incorporating the relationship between damage and loss of strength from consideration of mechanics. Therefore, a new crack width-based visual damage assessment method for RC frame buildings is presented. Critical levels of damage in RC members are defined based on mechanics and failure modes and related to strain limits and residual crack width by simulation of experimental results.

2. Critical member damage states

Under earthquake excitation, the behavior or performance of RC member is mainly governed by condition of confining reinforcement. The concrete strain comprises of ascending and descending branches (Park and Paulay [10]). For under reinforced concrete members with low axial load ratios (less than 0.4), yielding of reinforcement generally occurs in the ascending portion of the stress-strain curve of the concrete. The member experienced minor but irreversible flexural cracking in this phase. For a section with flexural cracks, shear force is transferred through truss action. The concrete in the compression zone, transverse reinforcement in inclined crack zones and aggregate interlocking provide sufficient shear resistance to avoid brittle failure. Thus yielding of longitudinal reinforcement or cracks in cover concrete corresponding to compressive strain limit of 0.002 (~0.002 k) is treated as slight damage state. As strain increases, concrete stress-strain enters into descending portion. The initiation of cover concrete spalling occurs in this portion. The spalling of concrete reduces the shear resistance of concrete by destroying the bond between reinforcement bar and concrete. Although, the shear resistance provided by transverse reinforcement and aggregate interlocking is sufficient to ensure gravity load transfer; a significant reduction in lateral resistance of the complete building results when a large percent of joints experience this level of damage. A detailed engineering evaluation and suitable repair measures are generally required to retrieve loss in lateral resistance. Thus, initiation of spalling of cover concrete is classified as moderate damage to the member.

Significant spalling of cover concrete, that occurs subsequently, indicates spreading of crack across the core concrete. The cracks across the core concrete severely affect the shear resistance from aggregate interlocking due to grinding and gradual smoothening of the crack interface under repeated loading and leads to a rapid reduction in strength and stiffness of the member (Penelis and Kappos [11]). At this stage, shear resistance is provided only by the transverse reinforcement through dowel action. The transverse reinforcement yields under large loading and leads to buckling of compression longitudinal reinforcement bars. The buckling of longitudinal reinforcement of the columns causes a significant loss in gravity load carrying capacity of the building. Hence, significant spalling of cover concrete in compression members represents severe damage state and core crushing/longitudinal bar buckling indicates extensive damage state.

3. Available engineering limits for flexural damage states

Numerous studies are carried out to relate yield and ultimate damage states with response parameters such as extreme fiber compressive strain, curvature, chord rotation, and drift or displacement. Of these parameters, extreme fiber compressive strain is a convenient engineering response parameter to define critical damage states, as it directly proportional to tensile strain and maximum as well as residual crack width. Thus, in the present study, the critical damage states are related to extreme fiber compressive stress.

Priestley [12] proposed limiting the value of outer fiber concrete strain as 0.0040 at the onset of the crushing of concrete cover. Lehman et al. [13] observed mean strain value of 0.0066 with a standard deviation of 0.0022 for extreme fiber compressive strain at initial spalling and mean strain value of 0.0188 and standard deviation of 0.01 for compressive strain at crushing of core concrete. In another study, Chen et al. [14] reported mean extreme fiber compressive strain of 0.0063 and standard deviation of 0.0022 at initial spalling of cover concrete. From Lehman et al. and Chen et al. studies, the mean minus one standard deviation values of outer fiber concrete strain at initial concrete cover spalling and core crushing are 0.0044 and 0.0088, respectively. In the present study, the strain limits are investigated from the simulation of experimental data.

4. PEER database of experimental observations

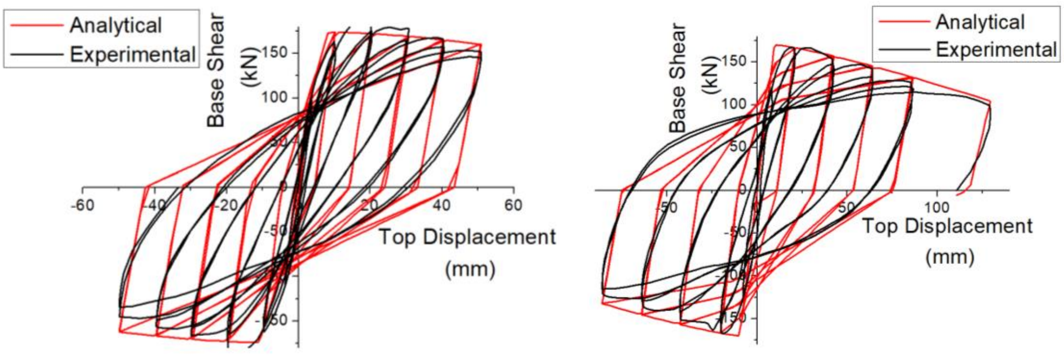
The Pacific Earthquake Engineering Research (PEER) Centre structural performance database [15] has compiled column properties, test configuration, force-displacement history, displacements and corresponding damage during cyclic lateral load tests on RC columns reported by a number of researchers. The displacements have been recorded at onset of spalling (first observation of spalling), onset of significant spalling (minor cracks in core concrete) and onset of bar buckling or fracture of transverse/longitudinal reinforcement.

4.1 Simulation of experimentally observed behavior

The authors have numerically simulated 33 rectangular columns from PEER database, having axial load ratio of 0.1 to 0.4, clear cover between 25 to 40 mm and flexural failure mode using IDARC-2D 7.0 [16]. The force levels are varied to simulate a full range of responses from undamaged to severely damaged behavior. Longitudinal (ρ_l/A_g) and confinement (ρ_w/A_g) reinforcement ratios of columns selected for simulation range between 0.0125 to 0.0239 and 0.0049 to 0.0324, respectively.

A trilinear moment-curvature relationship and spread plasticity model have been used for the simulation of experimental responses. The inelastic cyclic behavior of RC members is reproduced using non-symmetric three-parameter hysteretic models, proposed by Park et al. [17].

Fig. 3 compares experimental and simulated force-deflection relationships for Ang et al. (No. 3) (1981) and Tanaka and Park (No. 1) (1990) experiments from the PEER database. The simulated force-displacement relationships have an excellent match with the experimentally observed relationships. The difference between experimental and numerical simulated force-displacement relationships in the post-yield range is due to tri-linear approximation of continuous moment-curvature relationships. However, the value of parameters of interest, crack widths and compressive strains, are determined from the continuous moment-curvature relationship.



(a) Ang et al. no. 3, 1981 (b) Tanaka and Park no. 1, 1990

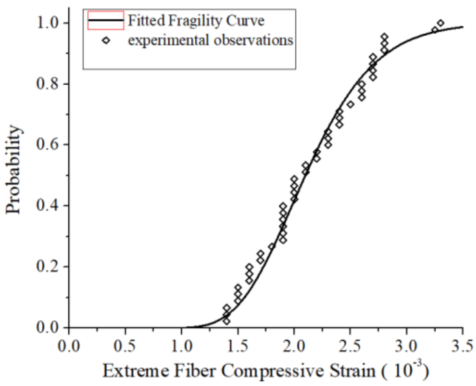
Fig. 1 – Comparison of experimental and simulated force-deflection relationship

The developed moment-curvature relationship and response characteristics used in the study reproduce experimentally observed nonlinear responses and are useful to determine values of compressive strains at critical damage states from the displacements recorded at observed damage states. The direct mapping between force-displacement and moment-curvature relationships is used to determine values of compressive strains.

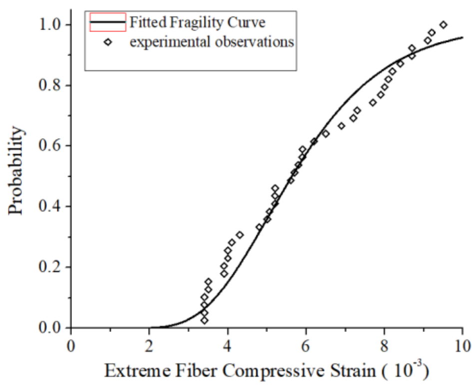
5. Compressive strain limits for critical member damage states

Simulated experimental force-displacement relationships have been used to determine the values of extreme fiber compressive strain and curvature ductility for the displacements recorded at observed damage states from PEER database. The mean value of extreme fiber compressive strain at first yielding of reinforcement, at onset of spalling (transverse reinforcement visible), significant spalling (longitudinal reinforcement exposed and concrete core visible with minor cracks) and bar buckling are 0.0019, 0.0055, 0.0091, and 0.0157 respectively.

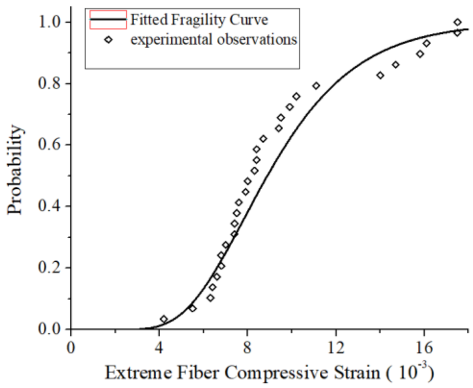
To determine the likelihood of occurrence these damage states, fragility functions of the compressive strains are plotted in Fig. 2. The limiting values of compressive strains at these damage states have been taken at 5% probability of exceedance. The 5% probability of exceedance has been selected to ensure conservative tagging of the damage states. The limiting values of compressive strains for the above-mentioned damage states are 0.0014, 0.003, 0.0045, and 0.0075, respectively.



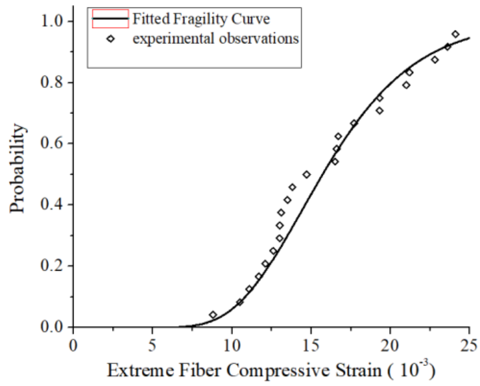
(a) First yield of reinforcement



(b) Onset of concrete spalling



(c) Onset of significant spalling



(d) Bar buckling

Fig. 2 – Fragility curves in terms of extreme fiber compressive strain at various damage states

The compressive strain limit at the onset of spalling is also very close to compressive strain at crushing of unconfined concrete prescribed by various design codes (about 0.003 to 0.0035). The onset of spalling (transverse reinforcement visible) representing a moderate damage state occurs between initiations of spalling and significant spalling. From the available strain-based definitions, it can be seen that the extreme fiber compressive strain value of 0.0044 represents the initiation of concrete crushing and strain of 0.0066 represents initial spalling of cover concrete. The compressive strain limit at significant spalling matches with the published lower limit of initiation of crushing. In order to identify the critical damage states during the post-earthquake visual survey, the correlation between damage states are residual crack widths are determined.

6. Crack width limits for critical member damage states

6.1 Estimation of residual crack width

The authors recently proposed new expressions to estimate the maximum flexural crack width and residual crack width in RC frame members under service loads (Shiradhonkar and Sinha, [18]). The expressions are developed from the principle of mechanics and are applicable to both linear and nonlinear response ranges. The expressions are also applicable for different levels of axial load and are thus applicable to both beams and columns of RC frame buildings. The following new expression is proposed to determine the maximum flexural crack width at a section in RC members.

$$\begin{aligned} W_{\max} &= 8.78\times10^{-6}\times\beta f_s \sqrt[3]{d_c A_e}, \text{ for } \eta_0 \le 0.15 \\ W_{\max} &= \left(1.00\times10^{-5} - 8.10\times10^{-6}\eta_0\right)\times\beta f_s \sqrt[3]{d_c A_e}, \text{ for } \eta_0 > 0.15 \end{aligned} \quad (1)$$

Where, f_s stress in tensile reinforcement (MPa), A_e (mm^2) and d_c (mm) are the effective stretched area of concrete and distance from the center of the reinforcement steel to extreme tension fiber of concrete, respectively. β is the ratio of the distance between the neutral axis and tension face of concrete to the distance between neutral axis and centroid of reinforcing steel. The residual crack width (w_{res}) at the end of excitation is expressed as a function of the maximum crack width (w_{max}) and curvature ductility at peak response (peak compressive strain). Following new expression is proposed to determine the residual flexural crack width

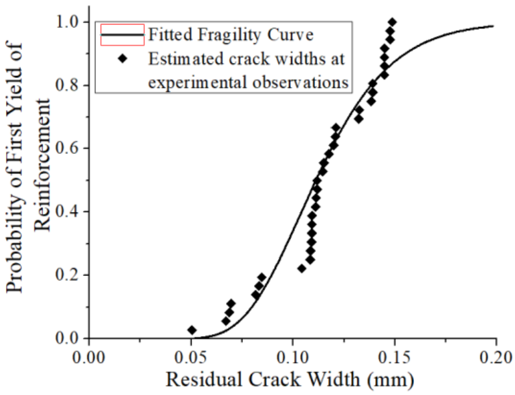
$$\begin{aligned} W_{res} &= 0.275\mu_\phi \times W_{\max}, \text{ for } \mu_\phi \le 2 \\ W_{res} &= 0.55\times W_{\max}, \text{ for } \mu_\phi > 2 \end{aligned} \quad (2)$$

In the earlier publication, the authors show that the residual crack width is not significantly affected by stress reversal imposed by cyclic loads. Thus, the above expression for residual crack width is applicable for a post-earthquake situation even though information regarding a number of load cycles is not readily available.

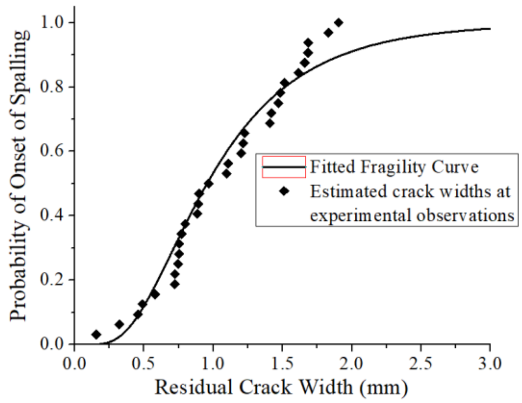
6.2 Proposed crack width limits

For simulated of PEER database observations, residual crack widths at first yield of reinforcement, onset of spalling, and onset of significant spalling are determined using Eq. 2. The median values of residual crack widths at first yield of longitudinal reinforcement, onset of spalling, and onset of significant spalling are 0.11 mm, 0.95 mm and 1.78 mm, respectively. The corresponding lognormal standard deviations are 0.26, 0.55, and 0.56, respectively.

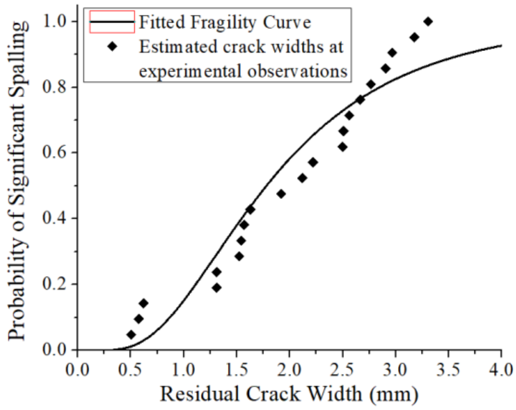
Fragility functions of critical damage states in terms of residual crack widths limits are plotted to determine the likelihood of occurrence of these damage states from visual observations. Figure 5 shows residual crack widths from simulated experimental database and fitted lognormal CDF for critical damage states. The fragility functions shown in Fig. 3 are useful in two ways. First, it is useful to set out limiting values of residual crack widths for the chosen value of probability of exceedance. The limiting values are useful for the classification of damage during post-earthquake visual survey. Secondly, the fragility functions are useful to determine the probability of damaged member being in different damage states for observed residual crack width of the damaged member.



(a) First yield of reinforcement



(b) Onset of concrete spalling



(c) Onset of significant spalling

Fig. 3 – Fragility curves in terms of residual crack width limits at various damage states

The limiting values of compressive strains (estimated from Fig. 4) and residual crack widths at different POEs are summarized in Table 2. After significant spalling of concrete cover, residual crack width limit is not found suitable to identify severe and collapse damage states. Occurrence of bar buckling is identified from observation of the extent of visual damage. The median values of compressive strains from observed states are closer to the mean compressive strains reported in the literature.

Table 2–Values of compressive strain and residual crack widths at critical damage states at different probability of exceedance

Probability of non-exceedance	**Compressive strain**				**Residual crack width (mm)**		
	First yield	**Initiation of spalling**	**Significant spalling**	**Bar buckling**	**First yield**	**Initiation of spalling**	**Significant spalling**
5 %	0.0014	0.0033	0.0048	0.0096	0.070	0.250	0.725
10 %	0.0016	0.0037	0.0057	0.0108	0.080	0.375	0.875
50 %	0.0021	0.0056	0.0088	0.0156	0.120	0.975	1.800

The probability of exceedance to set out the limiting values of residual crack widths can be determined based on the objectives of the visual survey. The primary objective of the post-earthquake visual survey is to ensure the safety of occupants under probable aftershocks. Thus, loss in the load-carrying capacity of the building shall be very small. Limiting values of member damage states shall be stringent to address both the aleatory and epistemic uncertainty associated with classification. Thus, the limiting values can be set up at 10% POE. If the objective of the visual inspection is to choose repair or retrofitting scheme, to restore or enhance the performance of the damaged building or to calculate economic losses then the limiting values can be determined at 50% POE i.e. at the median value. On the other hand, damaged buildings, which are necessary to occupy for a limited duration after an earthquake, can be assessed using limiting values determined at POE between 10% to 50 %.

In the present study, the limiting values of the parameters at critical member damage states are determined corresponding to 10% POE. The 10% POE is chosen to ensure a conservative estimate of the residual capacity of the building from a visual damage survey for generic building typology. The limiting values of residual crack widths at critical damage states for 10% probability of exceedance are 0.08 mm, 0.375 mm, and 1.00 mm, respectively. The values of compressive strains for the same probability of exceedance are 0.0016, 0.0037, 0.057, and 0.0108, respectively.

Fragility functions of compressive strains (Fig. 4) are used to determine POE of all critical damage states corresponding to the above listed limiting values of compressive strains, are summarized in Table 3. POE of respective damage states is close to 10% for selected limiting values. Fragility functions of slight and light states are not overlapping, while those of moderate and severe are overlapping. For compressive strain limit of 0.0016, POE is 11.5% for slight damage, while POE is 0 for subsequent damage states. POEs are 10.2 % for light damage, 99 % for slight damage and 0.56 % for moderate damage corresponding to compressive strain limit of 0.0037. At moderate and severe damage state, POE for prior damage states is more than 50 % for limiting compressive strains 0.0057 and 0.0108, respectively. For selected limiting values probability of members in the higher state, which indicates non-conservative assessment, is extremely small.

Table 3 –Probability of exceedance of different damage states corresponding to limiting values of compressive strains

Compressive strain	**Probability of exceedance (%)**			
	DS1-Slight	**DS2-Light**	**DS3-Moderate**	**DS4-Severe**
0.0016	**11.47**	0.00	0.00	0.00
0.0037	**99.00**	**10.21**	0.56	0.00
0.0057	99.99	**53.59**	**11.37**	0.03
0.0108	100	97.50	**71.02**	**9.80**

7. Proposed crack width-based visual member damage states

Proposed limiting values of residual cracks for identification of critical member damage states during visual survey are presented in Table 4. POE of critical damage states at proposed residual crack widths are also summarized in Table 4. The proposed residual crack width limit ensures nearly constant POE at all the critical damage states.

Table 4 – Proposed damage classification and crack width limits for structural members

Rank	**Damage description**	**Residual crack width (mm)**			
			DS-1	**DS-2**	**DS-3**
I - Slight	Visible but narrow cracks on surface of concrete	0 – 0.10	**0-30**	0-0	0-0
II - Light	Visible clear cracks on surface of concrete	0.10 – 0.40	30-100	**0-11**	0-0
III - Moderate	Local crush of covered concrete, onset of initial spalling (transverse reinforcement exposed)	0.40 – 1.0	100-100	11-70	**0-14**
IV - Severe	Significant spalling (longitudinal reinforcement and core exposed), minor cracks in core concrete	> 1.0	100	50	15
V - Collapse	Core concrete crushed and buckling of reinforcement bars	Criteria not suitable to differentiate between class IV and V			

8. Summary

The paper presents a new member damage classification that can be used for post-earthquake visual damage assessment as well as in the aseismic design. The classification method has been developed based on the mechanics of damage progression in RC members and their relationship with the residual seismic capacity. It had been found that while the prevalent crack width-based classifications are very convenient to use during post-earthquake damage assessments, they may not have sufficient accuracy during moderate damage conditions. It is also found that the prevalent methods do not explicitly consider engineering response parameters and the extent of reduction in lateral load-carrying capacity.

In the present study, experimental results have been numerically simulated to determine compressive strain limits and residual crack width limits for the observed damage states. The limiting values of compressive strains and residual crack widths are determined from the fragility functions. Based on these investigations, a new member damage state definition addressing a wide range of moderate damage states has been proposed in terms of residual crack width limits. Fragility functions in terms of residual crack widths are useful to determine limiting values based on the objective of a visual survey. In the present study, the limiting values of residual crack widths are established at 10 % POE to ensure a conservative estimate of the residual capacity of the building from visual damage survey. The proposed residual crack width limit ensures nearly constant POE at all the critical damage states.

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