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DEFINING VULNERABILITY SCORE MODIFIERS FOR PARAMETERS THAT AFFECT RAPID VISUAL SURVEY SCORE: A NUMERICAL STUDY

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Abstract

It is well known that loss of life during an earthquake event is mainly due to collapse of buildings that are not designed, executed or maintained properly. Therefore there is an urge for pre-earthquake vulnerability assessment of buildings in moderate-to-severe earthquake prone areas world-wide. Vulnerability assessment of a building is a challenging task and it has to be dealt very carefully. However, for large number of buildings in a city or town, some simple methods have to be employed. Rapid Visual Survey (RVS) is one such method which is widely used all over the world. It uses many parameters like presence of soft storey, plan irregularities, stiffness irregularities, short-column effect, etc., for evaluating the score. This score has a limitation because the forms that are developed at one place cannot be used in different region, due to large variation in design guidelines and construction technology and hence it is important to develop forms which are specific to an area and also building technology used. In addition, it is also important to calibrate RVS scores to possible damage indicators. Hence it is important to know the effect of individual parameter (i.e., vulnerability score modifier) on the overall score. This paper describes the numerical procedure for defining the value of vulnerability score modifiers for parameters that affect RVS score.

Keywords: Rapid Visual Screening; Vulnerability Score Modifiers; Numerical Analysis

1. Introduction

From the past records of many earthquake damages till the recent 2015 Nepal earthquake, the vulnerability of existing buildings is highlighted. It also demands the attention which is required for the safety of existing building stock in high seismic zone areas in many countries. After many attempts, it was observed that more reliable and quick procedure was needed to identify the most vulnerable structures from the stock buildings spread over large areas. In California, a point scoring method was first proposed in mid-seventies by Shah and Boissonnade [9]. Then a rapid visual screening (RVS) method was developed by FEMA 154 in mid-eighties. Later many countries developed their own RVS methodologies which are region specific and also based on many design parameters.

As per the International documents, mentioned in BMTPC report [10] the rapid assessment methods can be used in two different ways: (a) *Rapid assessment before earthquake* for understanding earthquake risk and creation of earthquake scenario to extrapolate damage in a seismic event of particular intensity. (b) *Rapid assessment after an earthquake* to decide whether the particular building in an earthquake affected area can be occupied or not.

A typical RVS form contains various questioners which are regarding the presence or absence of particular design parameter or vulnerability parameter in the building. Each of the vulnerability parameter has one assigned score values known as *vulnerability score* and each building type has one assigned score value known as *base score value.* Final summation of base score value and the vulnerability score values decide the most probable damage state of building during or after the event of earthquake.

The main objective of this paper is to develop a numerical procedure for assigning the score modifier value to the vulnerable parameters. The purpose of this procedure is to find out how each vulnerable parameter is contributing and by what amount, if a building is collapsed or having severe damage. This numerical procedure mainly requires the (i) building classification, (ii) capacity curve, and (iii) damage pattern in the building due to each vulnerable parameter. For the first part this paper focuses only on the RC Framed buildings. The third part the study of damage patterns in the structure to define score values is the main part of the study.

2. Review of Score Defining Procedures

During field survey the score values assigned to each vulnerable parameter plays a major role in deciding the performance of any building or a structure which in future helps in decision making. So the score defining procedures should aim to expose the structural as well as non-structural deficiencies in the building with appropriate weights. These procedures can be either analytical, empirical, numerical, hybrid or sometimes based on expert's opinion.

2.1 Score Defining Procedure in India

For the Indian subcontinent, various RVS forms are available which are developed by organizations such as BMTPC (Building Materials and Technology Promotion Council) as well as academic institutions.

The RVS form developed by the BMTPC is an outcome of a project which is related to the study of seismic safety of different housing typologies in India especially in moderate to severe seismic zones. After the intensive field survey it offered a base-level technical evaluation method. The method provides both seismic safety index and performance rating to a particular house with respect to an ideal house of the same typo [1]. The seismic safety index is defined for each vulnerable parameter for each of the housing typology. These index values or the score values for each parameter are based on the *Delphi-Method*. Delphi method includes only expert's opinion and no empirical or analytical procedures are involved in it. Experts based on previous study and his/her experiences give some score values to each parameter. Further the form clearly divides the all parameters into two factors that is *Life Threatening Factor (L)* and *Economic Loss-Inducing Factor (E)*. Each of these two factors is again divided into two more factors such as *Structural Element-related Factor* and *Non-Structural Element-related Factor*. So along with the score values the weightage to the parameters of *L* factors are given in such a way that presence of any one factor does not allow surveyor to go for *E* factors thus concluding that building is more vulnerable and needs urgent attentions.

The score assignment procedure adopted by S.K Jain and Keya Mitra is type of observed vulnerability assessment method, based on the statistics of damages of 2001 Bhuj earthquake [2]. The information recorded includes all possible vulnerabilities that could have caused damage to the building and detailed damage data. Initially for statistical study, performance scores were assigned to each building based on the damage level. Also variables were assigned to each vulnerable parameter and various variable selection techniques were used. Then the correlation was observed between the performance scores and vulnerabilities.

$$EPS = A + C_0x_0 + C_1x_1 + C_2x_2 + C_4x_4 + C_5x_5 + C_7x_7$$

In above equation term EPS represents the Expected Performance Score of a building. x_i being the vulnerability parameter, the buildings are categorized into a fixed number of damage groups And finally a multi-linear regression analysis was performed. C_i represents the score value of that particular vulnerability parameter. The procedure gives score values fairly, based on statistical analysis.

The RVS method proposed by Indian Standard drafted in IS 13935, 2004 uses damageability grading system. The code emphasis more on identification of construction materials, architectural features, load resisting system and falling hazards i.e., non-structural elements and does not involve any calculations. Based on these parameters and observed damage levels from the past earthquakes, buildings are graded between type A to D (A being the most vulnerable building and D being the least vulnerable building) in line with the MSK scale intensity. This grade assigning procedure is also based on *Delphi-Method*.

The RVS method developed for nearly 10 different housing typologies in India by Sinha and Goyal in 2004, requires to identify the load resisting system as well as building attributes that affects the overall performance of building [3]. This RVS method follows the exact procedure described in FEMA 154, 155 documents which is analytical method that follows capacity spectrum based approach. One advantage over the use of Sinha and Goyal's RVS form is that unlike FEMA procedure, the form clearly correlates the final score of the building with the most probable performance of the building i.e., probable damage grade which the building might experience during or after an event of earthquake. The final RVS score *S* of value less than 0.3 being the high probability of *Grade 5* damage and score more than 3.0 is less probability of *Grade 1* damage. These damage grades are based on European Macro-seismic Scale (EMS-98) which describes *Grade 1* damage as negligible damage and *Grade 5* damage as very heavy structural damage.

2.2 Capacity Spectrum method for Defining Scores

This particular method was first developed in United States of America which is explained in FEMA 154 and 155 documents. The procedure is also being used widely by different countries to develop their RVS forms. It requires the capacity curve and the demand curve for the selected building type and region. These two curves are then combined to generate the fragility curves for each building class which are provided in *Earthquake Loss Estimation Methodology Technical Manual, HAZUS99 Service Release 2.0.* The earlier editions of FEMA used these curves to develop the Base score for each building class as well as score modifiers, whereas for few vulnerable parameters such as plan irregularity and vertical irregularity, engineering judgement was used. The base score and score modifiers are calculated by determining probability of collapse, and then converting this to a score, *S*: [4, 5, 6]

$$S = -\log_{10}(\mathrm{P[Collapse}|MCE_R\ ground\ motions])$$

The main difference between the old procedure and the latest procedure is that, the latest edition of FEMA 155 is using the fragility curves that are provided in the modified version of *HAZUS99* document. Also the base score and score modifier values those appeared in old versions were calculated using 2/3 of the MCE values but in latest edition the demand is based on the full value of MCE. The score modifier for vulnerable parameters such as plan irregularity and vertical irregularity were also defined by using full MCE value. At the end this FEMA procedure does not correlate the final RVS score of building with the damage grade but do suggest whether the particular building requires detailed evaluation or not.

2.3 Score Defining Procedure in Canada

Canadian score defining procedure is described in details in the *Manual of screening of buildings for seismic investigation* (NRC-IRC 1992) [6, 7]. The manual has introduced 15 building types and the procedure have been adopted based on the previous work done by the Applied Technical Council which is described in the previous section *2.2* with some additions. The screening procedure requires same information similar to FEMA 155in addition to that non-structural hazard, usage and occupancy to evaluate seismic priority index (SPI) for the building. The seismicity and soil condition is selected based on the hazard maps of the Canada. Unlike FEMA and like the Sinha and Goyal's RVS procedure, the Canadian RVS form correlates the final RVS score of the building with risk categories viz., low, medium and high priority. These divisions into low, medium and high priorities are somewhat arbitrary and depend on local resources and priorities as well as the kinds of buildings involved. The SPI score less than 10 suggests low priority and buildings with SPI more than 30 are of high priority and considered as potentially hazardous.

3. Methodology Adopted

Apart from the widely used analytical method and empirical method, here in this paper a complete new approach is adopted and that is numerical approach. For this SAP2000 software package is used for modelling and analysing different RC framed structures.

3.1 Numerical Modelling of Structure

The advantage of numerical modelling is that any type of the building can be modelled if all the geometric as well as material properties of that particular building class are known. In this paper as an initial step only reinforced concrete framed buildings are in focus. Accordingly to reduce the complexity and to study the exact behaviour due to the presence or absence of particular parameter, only 2-dimensional frames are modelled. The material properties for the all the frames are fixed as 25 MPa for concrete and 415 MPa for reinforcement. Geometric properties such as beam cross section and column cross section are not fixed and calculated for each frame based on external load applied and design requirement.

Along with the RC frames, some of the frames are also modelled using three struts to study the effect of infill on building performance. The off-diagonal struts out of three struts are connected to the column and beam at a distance α_m/2and it is given as [12, 13, 14]:

$$\alpha_m = \frac{\pi}{2}\sqrt[4]{\frac{4\,E_c I_c h_m}{E_m t\,\sin(2\theta)}}\ (mm)$$

Where E_c *and* E_m are material properties of column and masonry wall in MPa respectively, I_c, h_m and t are geometric properties i.e., moment of inertia of column height and thickness of masonry wall in m respectively.

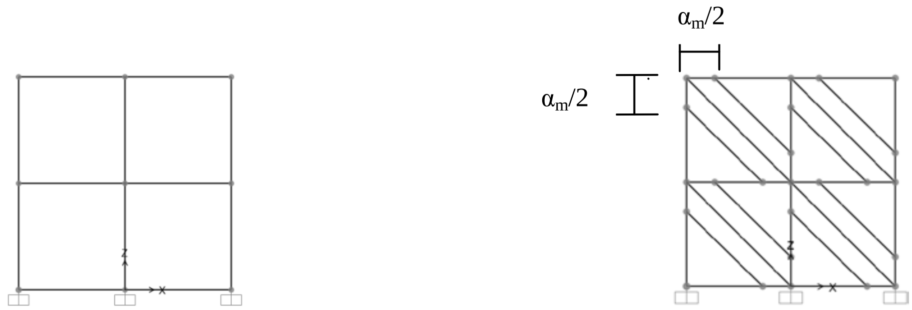


Fig.1 - Sample frames showing (a) RC bare frame and (b) RC infill frame with three struts

3.2 Analysis of Structure

For studying the behaviour of each frame and to do a comparative study both linear static as well as non-linear static analysis are performed. For linear static analysis gravity loads and lateral loads from equivalent static analysis are applied on the structure. The results (shear force and bending moment values) are then used to design the structural members which are then modelled in SAP2000 using section designer.

In non-linear static analysis which is also known as pushover analysis, a structure is pushed laterally until it completely fails or achieves desired displacement. In the current study displacement controlled pushover analysis is performed using the software package. For this, non-linear material properties also need to be applied on the RC members along with elastic material properties. Unlike elastic property, non-linear property is not distributed along the length of member but the lumped plasticity is defined at some locations on the member. During analysis flexure as well as shear hinges are defined for structural member. These plastic hinges are assumed to form at a distance equal to half the average plastic hinge length l_p from the member ends [12, 13]. l_p is calculated using following expression:

$$lp = 0.08L + 0.022 d_b f_y \ \ \text{(m)}$$

here L is length of member in m, d_b is diameter is longitudinal bar in m and f_y is yield strength of longitudinal steel in MPa. The strut is a replacement of masonry wall and it acts as a compression member as it takes only the axial forces. Therefore an additional axial hinges were assigned to all the struts. Due to axial force, the reaction will be same throughout the length of diagonal member and hence the location of axial hinge is fixed at the centre of length of strut.

3.3 Vulnerability Parameters

There are many vulnerability parameters that affect the building performance. Not all the parameters will reduce the building performance but some may add to the building strength or stiffness to resist the external loads. The vulnerability parameters considered in the present study are: beam-column joint, aspect ratio, short column, soft storey and vertical irregularity. Beam-column joints in RC moment resisting frames are the weakest portion because in most of the cases they are casted either using different materials properties or with improper beam-column cross section ratio, resulting in a limited strength and capacity. For analysing the effect of beam-column joint, the RC 2-dimensional frame is modelled with different I_b/I_c ratios i.e., ratio of moment of inertia of beam to column ratio.

Aspect ratios are of two type's viz., *Plan* aspect ratio (L/B) and *Vertical*/*Slenderness* aspect ratio (H/L). In this study only the effect of vertical aspect ratio i.e., H/L is considered. In some of the literature [15] the vertical aspect ratio was calculated as M/(Vb) where M and V are bending moment and shear force respectively and b is the width of building. 25 RC bare frames as well as 25 RC infill frames of different length and heights with vertical aspect ratios ranging from 0.2 to 5 are modelled and the effects are studied.

When the effective height of column in RC moment resistant frame is obstructed, the short column effect arises. As the lateral stiffness of column is inversely proportional to the cube of its height, this effect becomes more severe when unrestricted height of column is small [15]. To study this, RC frames with different short column heights are modelled. In the similar manner frames with different vertical irregularity [11] are also modelled to study their individual effects on frames. The above mentioned vulnerability parameter are individually modelled in 2-dimensional RC frames to observe each parameters contribution on building performance.

3.4 Initial Stiffness and Capacity Curves

After modelling and analysis the actual study begins with the analysis of the results. The initial stiffness values and capacity curves for each frame with the addition of individual vulnerability parameters are collected. From these two results a proper correlation between parameter and building performance is studied. The formation of plastic hinge pattern at each threshold points of the capacity curve was also observed to know the level of damage in each frame. This plastic hinge pattern involves the formation of flexure hinge as well as shear hinge.

3.5 Assigning Performance Score

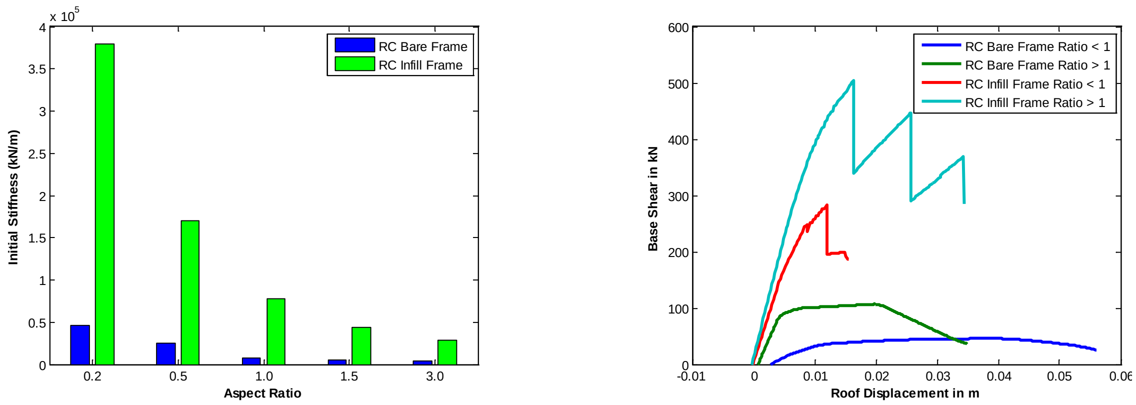
A non-linear static analysis i.e., pushover analysis determines the displacement capacity of a building which is expected to deform inelastically. A pushover curve is used to characterize a structure into two aspects viz., to know the ability of structure to dissipate the energy for particular displacement and the other is to know the roof displacement which is used by codal provisions as an overall capacity index of the structure. A cumulative dissipated energy function can be used to evaluate the damage [16].

$$Damage = \frac{E_i}{E_T} (1)$$

Here, E_i is the energy at any threshold point and E_T is the total energy of the structure which is calculated as total area under the capacity curve. Using the above relation with some modifications, the capacity or the limiting performance score at each threshold point is calculated.

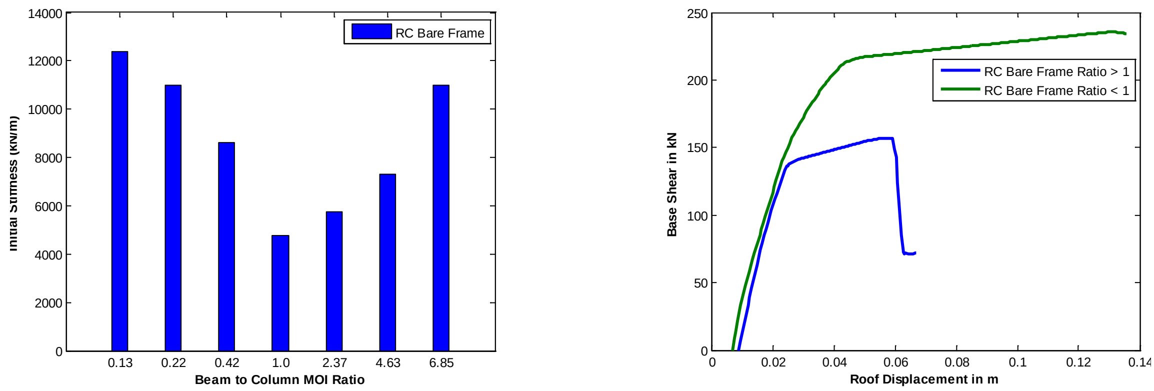
4. Results & Discussion

As discussed in above section, the capacity curves for the parameters are shown below. Figure 2(a) describes the comparison between the two frames: RC bare frame and RC infill frame. Plot also compares the aspect ratio for each type of frame and their initial stiffness values. As the aspect ratio is reducing, initial stiffness of frame is increasing. Aspect ratio is considered as H/L ratio.



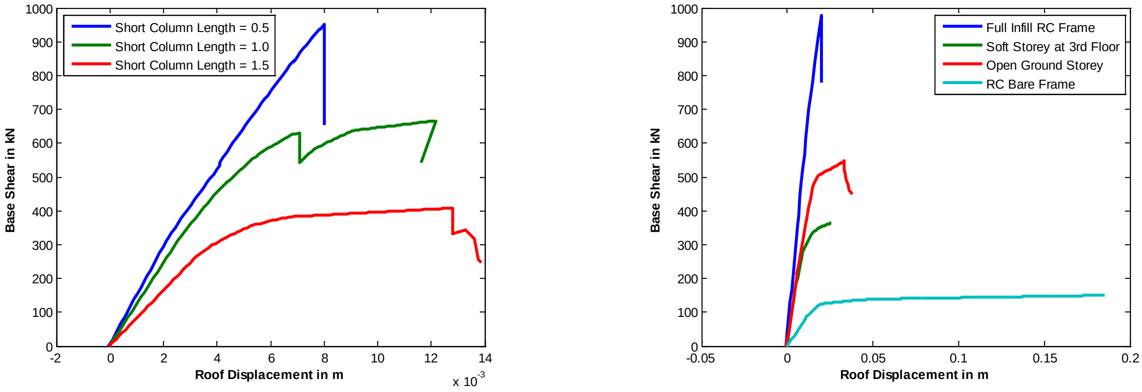
(a) (b)

Fig.2 - Comparison of (a) Initial Stiffness values (b) Capacity Curves between RC bare &infill frame for different Aspect Ratios



(a) (b)

Fig.3 - Comparison of (a) Initial Stiffness values (b) Capacity Curves between beams to column MOI ratios for RC bare frames only.



(a) (b)

Fig.4 - Comparison of Capacity curves for (a) different short column lengths, and for (b) different types of vertical irregularity

Therefore when H/L ratio is small, the lateral spread of the structure is more resulting in higher stiffness and more resistance and vice-versa. The similar kind of results can be expected from the figure 2(b). Smaller the aspect ratio more will be the lateral resistance which will result in higher base shear value and capacity of the structure. RC infill frame with aspect ratio less than 1 and also with additional diagonal strut members has much higher capacity compared to other frames. Therefore we can say that the parameter aspect ratio either adds to the capacity of structure or reduces based on the shape of building.

The beam-column joint is indirectly related to the strong column-weak beam and strong beam-weak column concept. Generally when the column cross sections are much greater than the beam cross section then it's a strong column weak beam concept and vice-versa. Here to study the same RC frames with different ratios of moment of inertia of beam to column are modelled. From figure 3(a) it is clear that even if the I_b/I_c ratio is more than 1 or less than 1, initial stiffness of the frame will not differ much. And it will be least for ratio of 1. Thus initial stiffness values are not giving so much of information. In figure 3(b) only two capacity curves are shown for clear understanding. It shows two different types of failure. The RC frame which is having ratio more than 1 is undergoing brittle failure and other one is ductile failure. Columns carry axial loads and fails by crushing if not properly designed which is brittle/sudden failure. Therefore the presence of same parameter is adding or improving the performance of the building given that I_b/I_c ratio< 1 and vice-versa.

It was observed from the analysis that there is no significant change in the initial stiffness values of all the frames with short column. Therefore only capacity curves are shown in figure 4(a). From figure 4(a) it is more clear that as the length of short column reduces amount of damage in the building increases. This is because deformation demand gets amplified on short column under lateral loading. Therefore presence of short column will always reduce the overall building performance which again depends on the height of short column.

If a capacity curve of any structure is known then using equation 1, the damage can be easily calculated. With little modification in the same equation as below, the retaining strength or capacity at each threshold point can be calculated easily.

$$Strength = 1 - \frac{E_i}{E_T} (2)$$

To use the above relation, initially capacity curves of all the 25 RC bare frames are plotted and threshold points on each curve are defined. Then using equation 2 the strengths at all the threshold points are calculated. The limiting value for the damage states are calculated by taking the average of all the values at that particular point. These values are tabulated in table 1.

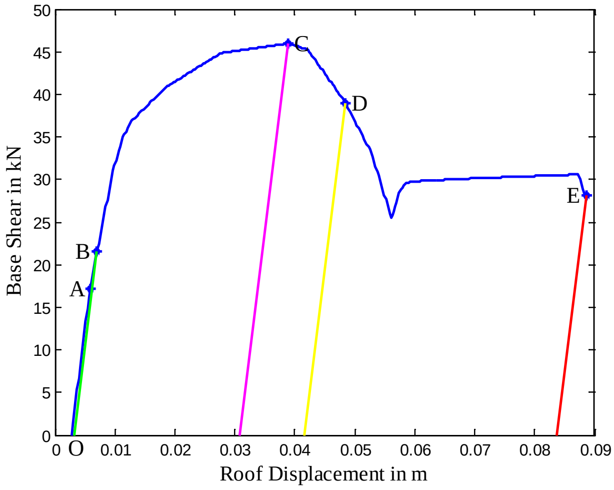


Fig. 5 - Defining strength at each threshold points

Table 1 - Description of damage levels and corresponding strength values

Threshold Points	Damage Level	Strength/Capacity
OA	No damage	100
AB	Slight damage	~ 90
BC	Moderate Damage	~ 70
CD	Severe Damage	~ 50
DE	Complete Collapse	0

5. Summary and Conclusion

The work presented in this paper is a first attempt for defining score values to the vulnerability parameters of RVS form using the numerical study. The vulnerability parameters (beam-column joint, aspect ratio, short column and soft storey) are individually modelled in a 2-dimensional reinforced concrete frame. The capacity curves which are generated to study the effects gave some sound relationship between the vulnerability parameter and the probable level of damages in each frame. The equation presented to calculate the capacity or the performance score clearly defines the damage states as well.

In the current available RVS forms the score value for particular parameter is either defined from the statistics of building damages from the actual earthquake scenario or by simply taking the difference of base score and base cases. Neither of these RVS procedures clearly states the exact contribution of individual vulnerability parameter in building's failure of collapse. So the proposed numerical procedure aims to define not only the vulnerability score but the exact weightage of each parameter in building performances. The procedure may also be helpful in future for decision making and to others for preparing new RVS techniques.

Further, the work presented in the paper till now did not mention any score values so far. Therefore the next step in the development of this work will be the assignment of score values and score modifiers to each vulnerable parameter taking into consideration the weightage factor. Calibrate or correlate the final RVS score of the building with most possible damage level or damage indicator. In addition to this, future work also aims in finding out the score values or modifier value for the building having two or more vulnerable parameter using the same numerical approach.

6. References

[1] C.V.R.Murty, Durgesh C. Rai, Hari Kumar, KeyaMitra, Amit K. Bose, Hemant B. Koushik, ArvindJaiswal, R. Pradeep Kumar (2012): A Methodology for documenting Housing Typologies in a Moderate-Severe Seismic Zones. *The15th World Conference on Earthquake Engineering*, Lisboa, Portugal.

[2] Sudhir K Jain, KeyaMitra, Manish Kumar, Mehul Shah (2010): A Proposed Rapid Visual Screening Procedure for Seismic Evaluation of RC-Frame Buildings in India. *Earthquake Spectra*, **26** (3), 709-729.

[3] Sinha, R., and Goyal, A.(2004). *A National Policy for Seismic Vulnerability Assessment of Buildingsand Procedure for Rapid Visual Screening of Buildings for Potential Seismic Vulnerability*,Department of Civil Engineering, Indian Institute of Technology Bombay, India. Available at www.civil.iitb.ac.in/~rsinha/Vulnerability_Assessment.pdf.

[4] ATC, 2002*a*. Rapid visual screening of buildings for potential seismic hazards: a handbook. FEMA 154, 2nd ed. Applied Technical Council, Redwood City, California.

[5] ATC, 2002*b*. Rapid visual screening of buildings for potential seismic hazards: supporting document. FEMA 155, 2nd ed. Applied Technical Council, Redwood City, California.

[6] ATC, 2015*b*. Rapid visual screening of buildings for potential seismic hazards: supporting document. FEMA P-155, 3rd ed. Applied Technical Council, Redwood City, California.

[7] NRC-IRC, (1992): Manual for screening of buildings for seismic investigation. Institute for Research in Construction, National Research Council, Canada, Ottawa.

[8] Amin Karbassi, and Marie-Jose Nollet (2008): Development of an Index Assignment Procedure compatible with the regional seismicity in the province of Quebec for the rapid visual screening of existing buildings. *Canadian Journal of Civil Engineers*, ***35***, 925-937.

[9] S. Tesfamariam, and M. Saatcioglu (2008): Seismic Risk Assessment of Reinforced Concrete Buildings using Fuzzy Rule Based Modelling. *The14th World Conference on Earthquake Engineering*, Beijing, China.

[10] Project Report, (2015): Methodology for Documenting Seismic Safety of Housing Typologies in India. Building Materials and Technology Promotion Council, New Delhi, India

[11] Bureau of Indian Standards, (2002): Indian Standard Criteria for Earthquake Resistant Design of Structures – Part 1. *General Provisions and Buildings* (Fifth Revision), New Delhi, India

[12] Hemant B. Kaushik, Durgesh C. Rai and Sudhir K. Jain (2008): A Rational approach to Analytical Modelling of Masonry Infills in Reinforced Concrete Frame Buildings. *The14th World Conference on Earthquake Engineering*, Beijing, China.

[13] Paulay T.,, and Priestley M J.N., (1992): Seismic Design of Reinforced Concrete and Masonry Buildings. Wiley-Interscience, New-York

[14] Stafford Smith B., and Carter C. (1996): A Method of Analysis of Infilled Frames. *Proceedings of the Institutions of Civil Engineers*, **44**, 31-48.

[15] Y. Lu, R. S. Henry, and Q. T. Ma (2014): *Proceedings of the 2014 NZSEE Annual Conference.* Auckland, New Zealand.

[16] A. Vimala, and R. Pradeep Kumar (2015): Expanded Energy Based Damage Assessment of RC Structures. *The Indian Concrete Institute Journal (ICI)*. **89** (8), 18-22.