DAMAGE BASED LIFE of HISTORICAL CONSTRUCTIONS IN SEISMIC ENVIRONMENT

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ABSTRACT:

Historical Structures are an integral part of the heritage of a country. Hence in seismic prone areas earthquake risk assessment of heritage structures becomes even more necessary. A systematic approach is used for this purpose. This approach is based on the estimation of expected number of earthquakes at each source with the help of Gutenberg-Richter relation and time-dependent hazard model and the estimation of structural damage during each of these events. The ground motion at the site under consideration during a particular event may be characterized in the form of the Power spectral density function (PSDF). To account for the non-linear behavior of structure, stochastic linearization techniques may be conveniently used to find the equivalent linear system properties in case of SDOF system. Damage can be quantified numerically by making use of damage indices (DI). A case study has been carried out for illustrating the proposed model, and it has been shown how this may be used to determine the design force levels for maximum allowable damage at the end of the design life. For the present study Earthquake Risk Assessment of Qutb Minar and India Gate situated in Delhi is done. The risk computed can be used to arrive at the present day strength of the structure. From the risk computed and depending on the strength of the structure, decision can to taken where the structure has to be Strengthened or Retrofitted for the future Earthquake and to preserve the Rich Cultural Heritage.

KEYWORDS: Historical Constructions, Damage, Stochastic Linearization.

INTRODUCTION: Indian Subcontinent is one of the seismically active regions of the world. The seismicity of India can be divided into 4 groups: Himalayan Region, Indo-Gangetic Plain, Kutch-Kathiawar Region and the Peninsular India. Himalayas are one of the rare sites of Continent to continent collision and also tectonically very active belt. The high seismicity of the region can be observed from the past events occurred in the region.Depending on the past earthquakes Bureau of Indian Standards has prepared the Seismic Zonation map of India (IS-1893-2002), which divides the country into 4 different zones. As per the zonation map 57% of the country falls under high seismic zone. These maps do not consider the frequency of occurrence of earthquakes; hence they do not divide the country into regions of equal hazard and risk. For cultural heritage and other important structures, these maps act only as a guideline for the expected intensities. For those structures site specific seismic hazard maps have to be generated for use, in assessing the damage or to know its performance in case of future events. Seismic gaps along two-thirds of the Himalaya that have developed in the past five centuries, when combined with geodetic convergence rates of approximately 1.8m/century, suggests that one or more M=8 earthquakes may be overdue(Bilham, 2004). Delhi has a long seismic history being affected by earthquakes of local origin as well as those of Himalayan origin. Delhi, the capital of India and a city which played a very important role in the History of India, is dotted with many historically important structures. Therefore for the present study, we have assessed the damage potential for the structures in Delhi. The risk is assessed taking into account the Seismicity of the area, estimation of earthquake parameters using scaling relationship, and then finally computing the damage using damage indices. Gutenberg-Richter relationship (Gutenberg and Richter,1942) and time-dependent hazard rate(Todorovska,1994) is used to find out the number of earthquake events expected to occur in that area over a specified period from the various nearby faults. The ground motion at the site under consideration during a particular event may be characterized in the form of the Power spectral density function (PSDF). PSDF is estimated using the known scaling relationships for Fourier spectrum, strong motion duration and PGA in terms of parameters like magnitude, epicentral distance and geologic site conditions given by Trifunac and Lee (1985). Since the structure is assumed to undergo significant inelastic deformations during the most severe and moderately severe earthquakes, it is necessary to account for non-linear behavior of the structure. To account for the non-linear behavior of structure, stochastic linearization techniques may be conveniently used to find the equivalent linear system properties in case of SDOF system. Damage can be quantified numerically by making use of damage indices (DI). Among the many damage indices available, the Park and Ang model is considered as this damage index is a linear combination of the maximum ductility and the hysteretic energy demand imposed by the earthquake on the structure.

DELHI: GEOLOGICAL AND SEISMOTECTONIC SETUP

***Geological Setup*:** Delhi region is situated between latitude 28˚24′01″ - 28˚53′00″N and longitude 76˚50′24″ - 77˚20′37″E and approximately covers 1500 Sq.Km. It is bounded by the Indo-Gangetic alluvial plains in the north and east, by the Thar Desert in the west and the Aravalli hill ranges in the south.
***Seismotectonic Setup*:** For seismic activity evaluation and to generate site-specific time histories and spectra, it is common engineering practice to take an area of 250 – 300 Km around the site under consideration. The area in and around Delhi is highly criss-crossed by faults because of joining of various sets of tectonic units. It is seen that the Delhi region has a long seismic history being affected by earthquakes of local origin as well as those of Himalayan origin. The distributions of the epicenters of moderate earthquakes appear to follow a NE-SW trend correlated with the direction of major tectonic features of the region. It is difficult to associate the seismicity of Delhi with any particular tectonic unit. On the other hand, it is observed that a number of lineaments appear to be seismically active simultaneously but to different extent. Therefore, in order to carry out the seismic hazard analysis the seismic potential of all the tectonic features must be taken into consideration. But for our present study we have considered an area of 250Km around Delhi.

The number of Seismogenic sources in this region as mentioned in Seismo- Tectonic Atlas of India are:1)Aravalli Delhi Fold axes,2) Delhi – Haridwar Ridge, 3) Sohna Fault, 4) Moradabad Fault and 5) Mathura Fault.The earthquakes which have struck in and around Delhi (within 250Km) are as noted below: 1)1505 Delhi (not recorded), 2) 15th July 1720 – Delhi (Magnitude = 6.5), 3) 1st September 1803 – Mathura (Magnitude = 6.5), 4) 10th October 1956 – Bulandshahar (Magnitude = 6.7), 5) 27th August 1960 – Delhi (Magnitude = 6.0), 6) 15th August 1966 - Moradabad (Magnitude = 5.8).

1. SEISMICITY OF THE AREA: Seismicity means the expected rate of occurrence of earthquakes of different magnitudes. For a single source, the occurrence rate $\mathrm{N}_{lk}(\mathrm{M})$ of earthquakes with magnitudes greater than or equal to M is obtained by Frequency – Magnitude relationship given by Gutenberg – Richter (1942) as

$$Log\mathrm{N}_{lk}(\mathrm{M}) = a - b\mathrm{M} \tag{1.0}$$

Where ‘a’ and ‘b’ are constant characteristics of the source.
The number $\mathrm{N}_{lk}(\mathrm{M})$ obtained by Gutenberg-Richter equation is associated with some uncertainty and therefore it is to be considered as a Random Variable. The Uncertainty is associated with the knowledge of source characteristics and due to the random nature of earthquake occurrence. Since there are different data sets for a seismogenic zone, each data set would give different value of $\mathrm{N}_{lk}(\mathrm{M})$. Thus $\mathrm{N}_{lk}(\mathrm{M})$ has to be described by an appropriate probability distribution. One step memory models with a time dependent hazard rate such as Lognormal has been used to evaluate the Probability of occurrence. The return period is considered to be lognormally distributed such that for a given magnitude interval, the median of the(lognormally distributed)

return period is equal to the expected value of the exponentially distributed return period as in the Poissonian model(see Todorovska(1994)) The hazard rate, $h(t)$ of a probability distribution function $F(t)$ with density $f(t)$ is given by

$$h(t) = \frac{f(t)}{1 - F(t)} \tag{1.1}$$

Given that there has been no event for time t since the most recent event, the probability that there will be an event in the time interval $(t, t + \Delta t)$ is equal to $h(t)\Delta t$. The hazard rate for probability distribution function of the return period assumed to be Lognormal is given by $h_{LN}(t)$.

$$h_{LN}(t) = \frac{\phi\left[\frac{\ln t - \lambda}{\xi}\right]}{\xi\left(t - t\Phi\left[\frac{\ln t - \lambda}{\xi}\right]\right)} \tag{1.2}$$

Where ϕ and Φ are density and cumulative standard normal distribution functions. Where λ and ξ are the mean and standard deviation of the random variable, $\ln t$ where t denotes the return period. Further as suggested by Todorovska (1994), $\xi = 0.2$ may be considered to be a reasonable estimate.If there are no events during the time of T_o years since the last event, the number of occurrences of the M magnitude events on the source in Y years is given by

$$n\left(T_o + Y/T_o\right) = \int_{T_o}^{T_o+Y} h_{lk}(\tau)d\tau \tag{1.3}$$

2. ESTIMATION OF PSDF:

For estimating the damage due to all the events as predicted by the above equation, it is necessary to characterize the ground motion in terms of PSDF of the ground acceleration process for each event. Estimation of PSDF is done by using the known scaling relationships for Fourier Spectrum, strong motion duration, and PGA in terms of the parameters like earthquake magnitude, Epicentral distance and geologic site conditions. For the scaling of Fourier spectrum, the following scaling relationship as approved by Trifunac and Lee (1985) has been considered,

$$\log_{10} FS(T) = M + \mathrm{Att}(\Delta, M, T) + b_1(T)M + b_2(T)s + \frac{b_3(T)\Delta}{100} + b_4(T) + b_5(T)M^2 \tag{2.0}$$

Here, M is the earthquake magnitude, Δ is the representative distance from the source to station, and s (i.e. s=0 for alluvium, s=1 for intermediate and s=2 for rock) represents the site condition for desired combination of site and event.For the scaling of strong motion duration T_s following relationship given by Trifunac and Brady (1975) is used

$$T_s = -4.88s + 2.33M + 0.149R \tag{2.1}$$

It may be mentioned that besides relating the Fourier spectrum amplitudes with the PSDF amplitudes, the strong motion duration plays a key role in determining the total number of cycles and thus the structural damage during the earthquake excitation (Basu and Gupta (1995)).Assuming the ground motion to be a stationary process, the PSDF corresponding to the M magnitude event occurring at a source is calculated at frequency ω , as

$$G(\omega) = \frac{Z^2(\omega)}{\pi T} \tag{2.2}$$

Where, $Z(\omega)$ and T are the expected Fourier spectrum and strong motion duration for magnitude M and Epicentral distance R. considering a single degree of freedom oscillator, we obtain its linearized properties. After obtaining the Linearized properties ω_{eff} and ξ_{eff} the response PSDF can be computed as

$$E_{lk}(\omega) = \frac{G_{lk}(\omega)}{\left(\omega_{eff}^2 - \omega^2\right)^2 + \left(\xi_{eff}\,\omega_{eff}\right)^2} \tag{2.3}$$

From the response PSDF, $E_{lk}(\omega)$ the expected amplitude of the ith order response peak, i.e. $E\left[x_{(i)}\right]$ is estimated using the order statistics approach as proposed by Gupta and Trifunac (1988). From that approach we have

$$E\left[x_{(i)}\right] = x_{rms}\int_{-\infty}^{\infty} \eta p(i)(\eta)\,d\eta \tag{2.4}$$

3. DAMAGE MODEL:

For any screening or prioritizing process we need to estimate the probability of damage. Damage has to be defined if we need to estimate its probability. Structural Damage in a structure due to earthquake loading may be due to excessive deformation, or it may be due to accumulated damage sustained under repeated load reversals. From the available damage indices, the damage indices proposed by Park and Ang Model (1985)is considered. This model consists of simple linear combination of normalized deformation and hysteretic dissipated energy as

$$D_{lk} = \frac{x_m}{x_u} + \beta\frac{EH}{Q_y x_u} \tag{3.0}$$

Where x_m is the maximum displacement that the equivalent linear SDOF system would be subjected to during the base excitation, $x_u (= \mu x_u$ where μ is the available ductility) is the ultimate displacement of the system under monotonic loading, β represents the effect of cyclic loading on structural damage, EH represents the total energy dissipation in the structure during the excitation and Q_y is the yield strength of the structure. The first term accounts for pseudo-static displacement and the second term accounts for the cumulative damage. A hysteretic energy dissipation index E_h used to express the amount of hysteretic energy dissipation ΔW per cycle during a displacement reversal of equal amplitudes in the positive and negative directions. E_h is the hysteretic energy dissipation of the system. Following the modifications introduced in the model by Kunnath et al. (1992), following modified form has been considered in the study

$$D_{lk} = \frac{x_m - x_y}{x_u - x_y} + \beta\frac{EH}{Q_y x_u} \tag{3.1}$$

CASE STUDY 1: SINGLE DEGREE OF FREEDOM SYSTEM:

Using equation (1.0) to equation (1.4) for different magnitudes, the number of earthquakes within 50 yrs is found out to be as follows: The fault Parameters are taken to be a = 4.09 and b = 0.86.

From table-1 the numbers of events corresponding to the various magnitudes are known. And the maximum magnitude of earthquake that is possible because of the assumed fault is of Magnitude 6.5 and Epicentral distance is assumed as 30Km, s=0 for alluvium soil condition. Assuming the ground motion to be a stationary process, the PSDF corresponding to the M magnitude event occurring at a source is calculated at frequency (ω), using equation (2.2). A SDOF system is designed as per IS-456 and by adopting Gulkan and Sozen Linearization techniques the linearized properties of the SDOF system are found out. Using those linearized properties the response PSDF is estimated. From the response PSDF and using the order statistics approach as given by Gupta and Trifunac (1988) the number of peaks in the response are computed. Using the above computed values and the energy dissipated in the structure during the excitation, the damage is calculated. Fig 1.1 and 1.2 respectively show the Progressive increase in the expected damage, as indicated by the index D with the age of the structure for the design life Y = 25 and 50 yrs. The structure has been assumed to have 1.0 sec period, 5% damping, and has been designed based on the largest magnitude earthquake that is expected to occur during its design life. It is observed that with the increase in ductility values the damage is increasing. These trends are shown more clearly through a parametric study.

Table1: Average no of Earthquakes in 50 yrs.

Magnitude	No of Events	Average
4.0	370	7.4126793
4.5	248	4.9685773
5.0	151	3.0201368
5.5	77	1.5578986
6.0	29	0.5833033
6.5	4	8.86E-02
7.0	0	8.43E-05
7.5	0	3.29E-16
8.0	0	4.67E-38

For the parametric study, 28 SDOF oscillators with periods of 0.06,0.08,0.10,0.12,0.14,0.16,0.18,0.20,0.25,0.30,0.35,0.40,0.45,0.50,0.60,0.70,0.80,0.90,1.0,1.20,1.40,1.60,1.80,2.00,2.50,3.00,3.50,4.00 have been considered, and the variations of cumulative damage, design life, design ductility, have been studied with the variations in the oscillator time period. In each case, two of the other parameters have been kept at their default values while the third parameter has been assigned different values. The default values have been taken as: μ = 3, Y = 50 yrs, and damage index = 0.8. While the different values used for obtaining different curves are: μ = 2, 3, and 4; Y = 25, 50 and 75 yrs; and damage index (D) = 0.4, 0.6 and 0.8. Fig 1.3 to 1.9 show the various results obtained.

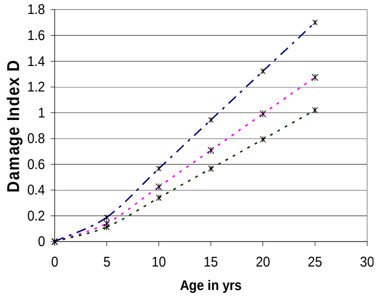

Fig: 1.1 Progressive Damage for SDOF Oscillator with 1 sec Period and ductility (μ) = 4, 5, 6.

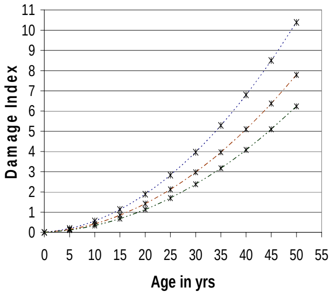

Fig: 1.2 Progressive Damage for SDOF Oscillator with 1 sec period and Y = 50 yrs and ductility (μ) = 4, 5, 6.

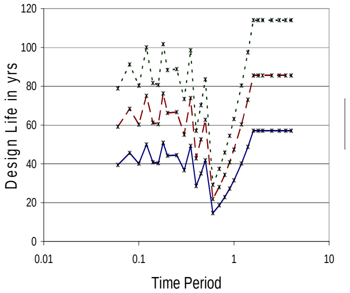

Fig: 1.3 Design Life of a set of Oscillators for an allowable Damage, D = 0.4, 0.6, 0.8, and ductility μ = 3.

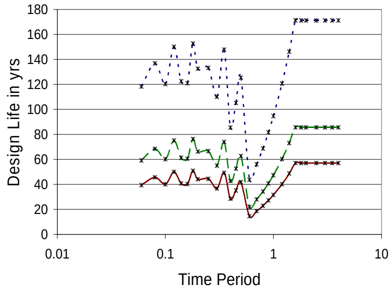

Fig: 1.4 Design Life of a set of Oscillators for ductility μ = 2, 3, 4. with D =0.6.

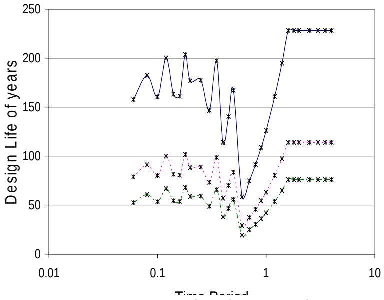

Fig: 1.5 Design Life of a set of Oscillators for ductility μ = 2, 3, 4. with D =0.8.

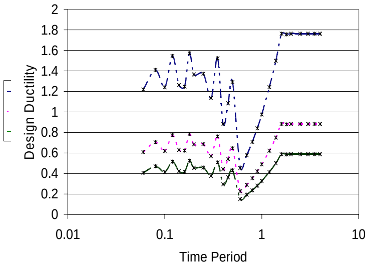

Fig: 1.6 Design Ductility of a set of Oscillators for design life Y=25, 50 and 75yrs and D=0.8.

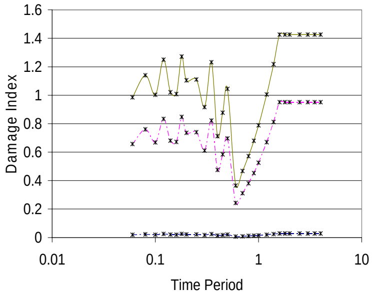

Fig: 1.7 Design Ductility of a set of Oscillators for design life Y= 50 and D =0.4, 0.6 and 0.8.

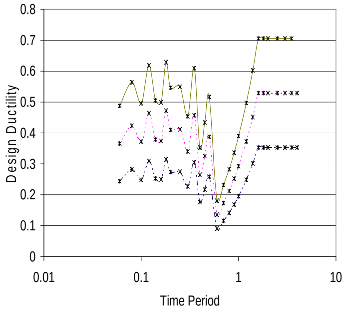

Fig: 1.8 Damage Index of a set of Oscillators for design life Y= 50 and μ = 2, 3, 4.

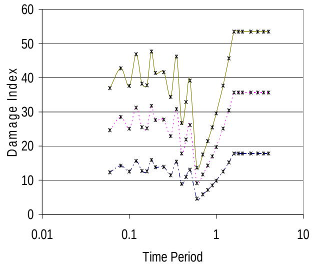

Fig: 1.9 Damage Index of a set of Oscillators μ = 3 and design life Y =25, 50 and 75 yrs.

CONCLUSIONS:

From the proposed formulation for the estimation of design life of SDOF structure which is situated in Seismic Environment. The structure is expected to attain a specified level of allowable damage at the end of its design life. With the help of the hypothetical example, the following conclusions are drawn. It has been found that the single event based conventional method of design may be inappropriate for ensuring safety in those areas where, besides the most critical earthquake, several earthquakes of milder intensity may also occur during the design life of the structure. For the usually adopted levels of force reduction from the linear levels, these earthquakes may generate sufficiently strong ground motions at the site of a structure so as to modify its response to be inelastic. Depending upon the damage levels considered acceptable in view of the functional requirement of the structures, the reductions in the linear response levels should be much smaller and be not governed by the ductility of the system alone.

CASE STUDY 2: HISTORICAL CONSTRUCTIONS:

In this Case-study, Damage Analysis of Qutb Minar and India gate both situated in capital city of India - Delhi are carried out, to check the effects of the earlier earthquakes and to evaluate its performance in case of any future earthquake event.

STRUCTURAL PROPERTIES:

a) Qutb Minar**:** The Qutb Minar directly rest on a 1.7m deep Ashlars masonry platform with sides of approximately 16.5m, which in turn overlies a 7.6m deep lime mortar rubble masonry layer, also square, with sides of approximately 18.6m. The bedrock is located around 50-65 m below the ground level. The minar cross-section is circular/polilobed, being the base diameter equal to 14.07m and tapering off to a diameter of

3.13m at the top, over a height of 72.45m. The tower is composed by an external shell corresponding to a three leaf masonry wall and a cylindrical central core. The core and the external shell are connected by a helical stairway and by 27 bracings composed of stone units. The stairway is spiral disposed around the central masonry shaft, and it is made of Delhi Quartzite stone. Each storey has a balcony and the uppermost storey finishes with a platform. The minar outer shell is composed by a three leaf masonry wall. In the first 3 storeys the external veneer is made of ashlars of red and buff colored sandstone whereas the internal is composed of Delhi Quartzite Ashlars. In the two upper storeys the external veneer is made of white marble stones and the internal of red sandstone. The infill is composed by rubble stone masonry, mainly with stone taken from the destroyed temples during the Islamic dominion.

b) India Gate**:** India Gate is located in Rajpath and was the first gate to be constructed in the New Delhi. It was built as a War Memorial to commemorate the death of 90,000 Indian soldiers, who were killed in the North West Province during the First World War and the Afghan Fiasco of 1919. The Duke of Connaught laid the foundation of this Memorial on 10th February 1921. The India Gate was designed by Sir Edwin Lutyens and was completed in 1931. The gate is built of sandstone rising to a height of 160 ft. the height of the arch is 136' externally and 87'6" internally. The entire arch stands on a low base of red Bharatpur stone and rises in stages to a huge cornice, beneath which are inscribed Imperial suns.

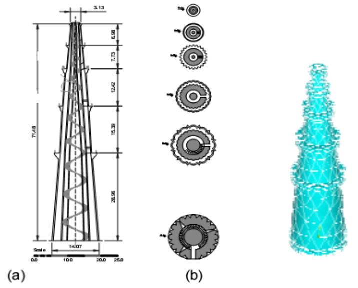

Fig 2: a) Vertical section of Qutb Minar
b) Cross section at different floors c) Finite Element Model

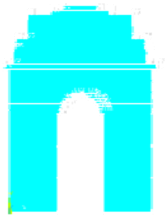

Fig 4: India Gate

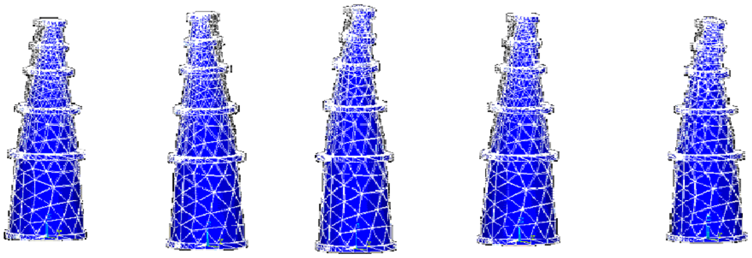

Fig 3: Modal Shapes for 3-D solid FE model.

PSDF COMPUTATIONS:

For various magnitudes the ground PSDF is estimated using assumed Epicenter distance as 30Km, s=0 for Alluvium soil condition. Assuming the ground motion to be a stationary process, the PSDF corresponding to the M magnitude event occurring at a source is calculated at frequency (ω), using equation (2.2). The ground PSDF thus obtained is used to find the response of the structure. From the response PSDF and using the order statistics approach as given by Gupta and Trifunac (1988) the number of peaks in the response are computed. Damage in a structure can be because of one of the following reasons.1) Damage can occur when the structure first goes beyond the yield limit, 2) During the phase of yielding and 3) Accumulation of damage due to each small but definite excursion.

We first computed the individual damage caused by each magnitude event, and then we take the cumulative sum of all the damages for all magnitude events. Using the above computed values and the energy dissipated in the structure during the excitation, the damage is calculated. The damage computations are done for each storey as well as for the whole structure.

LIMITATIONS OF THE PRESENT STUDY:

Since each monumental building is a unique building characterized with its own history, often resulting in a composite mixture of added or substituted structural elements strongly interacting , its often difficult to know the exact strength of the materials used .The deterioration of the structural elements in due course has to evaluated to arrive at the strength characteristics of the structure. For the present study the material characteristics are taken as per values given in EU report. The Park and Ang damage model adopted for the study is a reinforced concrete damage model. Since the structure is made up of Sandstone and Marble, the robustness of the Park and Ang model has to be verified before evolving at a consensus.

CONCLUSIONS:

As per the study the size of events occurring in Delhi region varies from 4.0 M to 6.5 M. During each such event the structure is allowed to go beyond its yield following an inelastic excursion. Each such inelastic excursion contributes in damaging the structure. Hence it is necessary to take into account all such contributions towards damage. Moreover it is a widely recognized fact that the structural damage due to earthquake does not depend only on maximum displacement but numerous inelastic excursions of relatively smaller amplitudes. Therefore it has been found that the single event based conventional method of damage computations may be inappropriate for ensuring safety where, besides the most critical earthquake, several earthquakes of milder intensity may also occur during the design life of the structure.

INTERPRETATION OF RESULTS FOR THE PRESENT STUDY:

***Qutb Minar*:** When Qutb Minar is subjected to all these individual ground motions and their cumulative effects are studied, we observe that its top two floors are more susceptible to damage.
***India Gate*:** When India Gate is subjected to all these individual ground motions and their cumulative effects are studied, we observe that its critical sections of failure are seen near the inner arch. The failure cracks start from inside arch and proceeds till the outer arch.

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