Decision Making for Structural Investment of Damaged Buildings after Abnormal Loadings

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Abstract: Seismic risk assessment of damaged buildings after abnormal loadings in the service life and decision making for the structural investment are presented in this paper. The purpose of the study is to obtain the decision measure whether the damaged building is reused or demolished after an accident case and to develop a quick safety assessment method for the remaining service period. The safety assessment of the six story reinforced concrete frame building considering future earthquake loading is considered in this study. The nonlinear static analysis (pushover analysis) by SAP2000 software simulation is used to determine the performance point of the case study building. Next, fragility curves of the damaged buildings and risk assessment are described and benefits for the reconstruction and repaired types are compared. The findings of this study highlight that the residual building which is physically stable in appearance after abnormal loading conditions should be checked against the natural hazard such as earthquake loading for the public safety and that the period of time at which the accident abnormal load occurs in the service life affect the benefits and decisions for the structural investment.

Key Words: abnormal load; decision; earthquake load; fragility; investment.

1. INTRODUCTION:

A structure could be subjected to abnormal loadings which may lead to element loss and in some cases to entire collapse in its lifetime. The potential hazards in the service life of a building are not only natural disasters such as earthquakes but also man made accidents such as vehicular collisions, severe fires, gas explosions, etc. Moreover, the accidents such as fire and explosions may follow after a natural disaster event and it is necessary to consider safety assessment of the damaged buildings. Therefore, it is a basic need to judge the safety of the residual building against the natural earthquake hazard after accident conditions.

Progressive collapse, local failure leading to a disproportionate failure of the building after an abnormal loading has been one of well-known problems among developers and structural engineers and updated guidelines has been published by the General Services Administration (GSA) and Department of Defense (UFC-DOD). People would leave immediately a collapse building, but it is not easy to decide to leave or stay in a partially damaged building which may stand physically stable after an accident. How much strength was lost and if it could be safe for future earthquake are interesting questions for the owners and state holders.

This paper provides a quick safety assessment method and decision measure whether the damaged building should be reconstructed or not. The safety assessment of the six story reinforced concrete frame building considering future earthquake loading is considered in this study. The nonlinear static analysis (pushover analysis) by SAP2000 software simulation is used to determine the performance point of the case study building. Next, failure probabilities of the damaged buildings and risk assessment are calculated and allowance for the reconstruction is estimated.

2. METHODOLOGY:

2.1. Data preparation for the analysis

The typical rectangular six story frame building with total three columns in short direction and four columns in long direction is analyzed for the study and the typical story height is three meter .Input data for analysis of the buildings are:

- fc′ = 3000 psi & fy = 40000psi
- Unit weight of concrete = 150 pcf
- 4-1/2inch thick Brick wall = 50 psf
- Superimposed Dead Load on floor = 20 psf
- Typical Floor Live Load = 40 psf

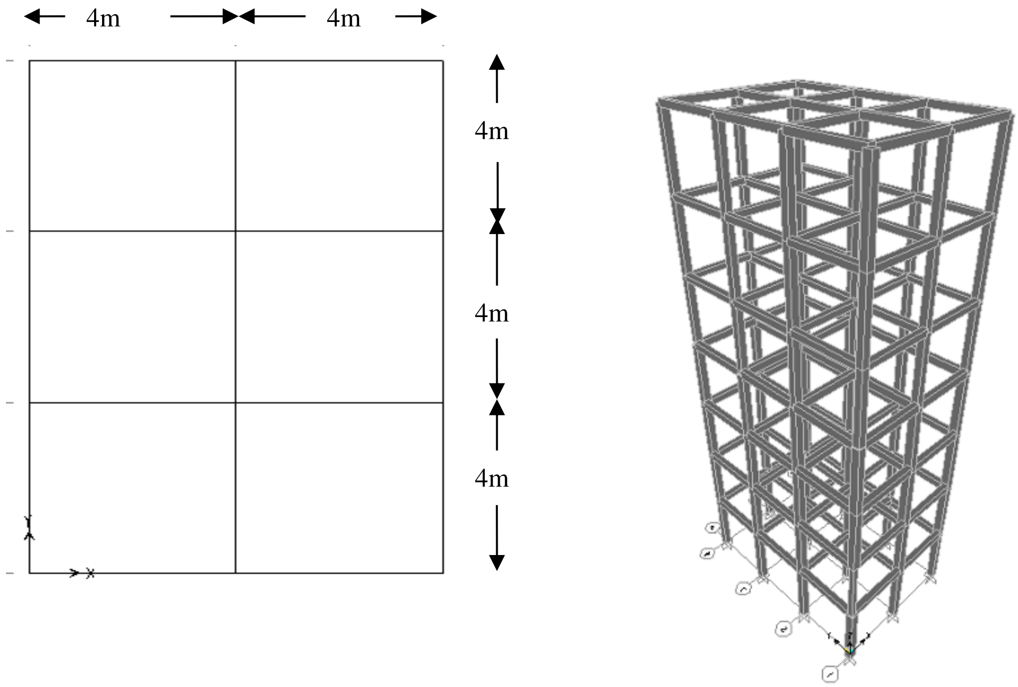

Figure 1: Typical Floor Plan and Three Dimension of the Hypothetical Model

2.2 Abnormal loading conditions

It is assumed that the energy is consumed by damages of structural element sizes in the analysis. In car crash cases, four cases are considered in the study since the number of damaged columns may vary with car types such as car, light truck, heavy truck, etc. Car collision study cases are as follow:

Case (1) = Analyze for 50% damage of one column section in the ground floor
Case (2) = Analyze for 50% damage of two column sections in the ground floor
Case (3) = Analyze for 50% damage of three column sections in the ground floor
Case (4) = Analyze for 50% damage of four column sections in the ground floor

For fire explosion case, possible occurrence locations are all floors. Suppose fire explosion occurs at a room and then the surrounding rooms will also be affected so that the column strength in its neighbors will be deteriorated. This effect can be assessed by introducing the column deterioration rate of the surround rooms such as 10% damage of the column sections. The study cases are as follow:

Case (A) = Analyze for 10% damage of all column sections in the ground floor
Case (B) = Analyze for 10% damage of all column sections in the sixth floor

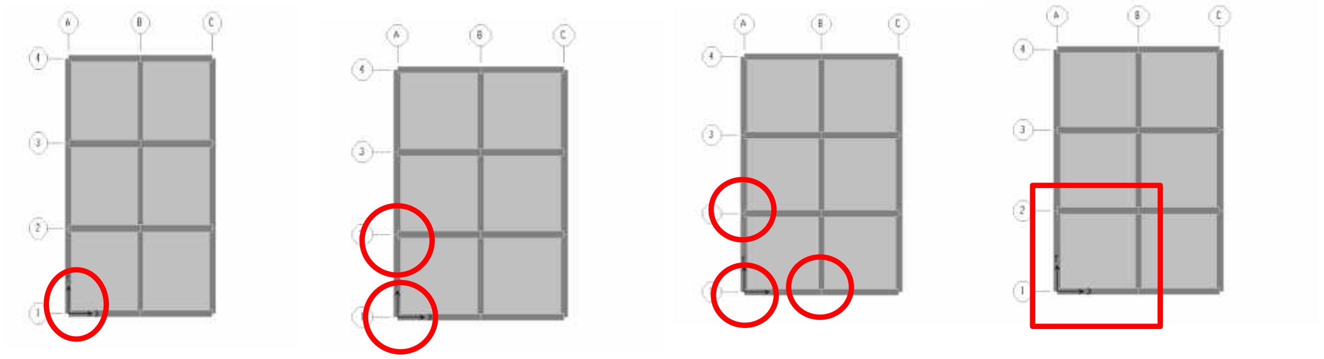

Figure 2: Case(1),Case(2),Case(3) and Case(4)

2.3 Seismic Load for Yangon Region

In considering earthquake hazard environment of Yangon City, the probability of exceedance in 50 years is 50% for the operational earthquake level (MOE), 10% for the design basic level earthquake (DBE) and 2% for the maximum considered earthquake level (MCE).

$$P = 1-[1- 1/T_R]^{n} \qquad (1)$$

Where, P = Probability of exceedance in 50years

T_R= Return period

The moment magnitude is expected from the Sagaing Fault and peak ground acceleration is calculated with the source distance, 45km.

$$\text{Ln (PGA)} = -0.152+0.859Mw-1.803\ln(R+25) \qquad (2)$$

Where, PGA = Peak ground acceleration

Mw = Moment magnitude

R = Source Distance

Table 1: Seismic hazard analysis for Yangon Region

Earthquake	MOE	DBE	MCE
Occurrence rate for fifty years, P_{50yr}	0.5	0.1	0.02
Return period, T_R (year)	73	475	2475
Moment magnitude, Mu	6.4	6.8	7.3
Epicentre distance, R(km)	45	45	45
Acceleration at the base rock(g)	0.10	0.14	0.21
Amplification, Cg	1.5	1.5	1.5
Acceleration at the ground surface(g)	0.15	0.21	0.32

2.4 Failure Probability of the Buildings

Generally, buildings are designed to resist normal loading conditions and failure would occur when the applied loading is beyond the strength of the structural members or the capacity of the building. It may say that the probability of failure of the building is the probability of the loading applied to the building greater than the resistance of that building. Therefore, it is the probability of the condition that the maximum roof displacement caused by loading condition is larger than the critical roof displacement of that building.

The critical roof displacements and performance levels of the buildings are directly affected by the amount of gravity and lateral loadings. The critical roof displacement at the roof level is approximately 2% of the building height in Design Basic Earthquake Level and the building would suffer it in life safety performance level.

Since all the design variables should be random, the statistical approach for the variables must be utilized to estimate the probability of failure. In order to do this work, the mean value and its standard deviation or equivalently coefficient of variation must be evaluated by using theoretical approach or numerical one such as Monte Carlo Simulation. Since Monte Carlo Simulation method takes much time to obtain the statistical values for several random variables in the limited period, it should take an alternative approach to get these data.

The statistical values (mean and standard deviation) of the maximum roof displacement can be calculated with simplified numerical method such as (μ_u, u_1, u_2) for the three surface ground motion such as (μ_{As}, $\mu_{As+\sigma As}$, $\mu_{As-\sigma As}$). The mean value and standard deviation of the roof displacements are obtained as

$$\mu_u\ ,\ \sigma_u = \frac{|u1 - u2|}{2}$$

for the operational, design and maximum considered earthquake levels respectively.

Once the statistical values of critical roof displacements and the maximum roof displacements have been estimated, one may calculate the probability of failure for the considered earthquake level as follows:

$$Pf = P\,[R < L] = P\,[R - L < 0] = P\,[Z < 0\backslash EQ] = 1 - \varphi\left[\frac{\mu_{ucr}-\mu_u}{\sqrt{\sigma_{ucr}^2+\sigma_u^2}}\right] \tag{3}$$

Where,

μ_{ucr} = mean value of the critical roof displacements

μ_u = mean value of the maximum roof displacements

σ_{ucr}^2 = variance of the critical roof displacements

σ_u^2 = variance of the maximum roof displacements

Abnormal loading conditions reduce either the strength or stiffness of structural members of the original buildings which leads to the poor frame behaviour of the damaged building. The probability of failure of the damaged building after the accident will be dependent on the damage level. It can be written in equation as follow:

$$p_f(d) = p[u_{cr} \le u_{\max}(d)] \tag{4}$$

Where,

P_f (d) = the probability of failure of the damaged building after the accident

u_{cr} = the critical roof displacement

u_{max} (d) = the maximum roof displacement of the damaged building

The damaged building should be demolished if it fails in progressive collapse and the building cannot support the normal gravity loading due to the severe accident condition. But it would need the restoration if the building is partially damaged and can support the normal loading condition safely after the accident. However, this building might have potential defect even after the restoration. Therefore, the probability of failure of the restored building is dependent on the potential defect.

$$p_f(c) = p[u_{cr} \le u_{\max}(c)] \tag{5}$$

Pf (c) = the probability of failure of the damaged building after the restoration

u_{cr} = the critical roof displacement

u_{max} (c) = the maximum roof displacement of the restored building.

2.5 Seismic risk management for the residual service life

The seismic risk of the building during the whole service period of *T* can be estimated by

$$Risk = \left(C_o + C_M\right) p_f\left(T, EQ\right) \qquad (6)$$

in which

T = the whole service period
EQ = an earthquake
$p_f(T, EQ)$ = the probability of failure under the condition of T and EQ
C_o = the initial cost
C_M = the maintenance cost during the whole service period of T

The probability of failure during the whole service period of *T* can be given by

$$p_f\left(T, EQ\right) = p_o\left(T, T_R\right) p_{fo}\left(EQ\right) \qquad (7)$$

where

$$p_o\left(T, T_R\right) = 1 - \left(1 - \frac{1}{T_R}\right)^T \qquad (8)$$

$p_{fo}(EQ)$ is the design probability of failure of the building for an earthquake *EQ*.

2.6 Risk assessment after the abnormal loading

Let assume the abnormal event occurs at T_A. The stakeholders of this building should discuss how to use this damaged building. Once the damaged building is decided to be used again in the residual period after the repair or re-construction, the revised risk is evaluated as

$$Risk^{*`} = \left\{ C_A + \frac{T - T_A}{T}\left(C_0 + C_M\right) \right\} p_f^{*`}\left(T, T_A, EQ\right) \qquad (9)$$

The probability of failure for the repaired building can be given by

$$p_f^*\left(T, T_A, EQ\right) = p_o\left(T_A, T_R\right) p_f^*\left(EQ\right) \qquad (10)$$

$$p_o\left(T_A, T_R\right) = 1 - \left(1 - \frac{1}{T_R}\right)^{T - T_A} \qquad (11)$$

$p_f^*(EQ)$ is the probability of failure of the damaged building for an earthquake, EQ.

3 RESULTS AND DISCUSSION:

3.1 Capacity curves for the damaged buildings

The overall capacity of a structure depends on the strength and deformation capacities of the individual components of the structure. In order to determine capacities beyond the elastic limits, some form of nonlinear analysis, such as the pushover procedure, is required. The pushover capacity curve approximates how structures behave after exceeding their elastic limit. Capacity curves of the considered six cases are shown in figure (3). This figure show that the capacity of the whole building reduces with the damage conditions and it is also depending on the location of the accident occurs.

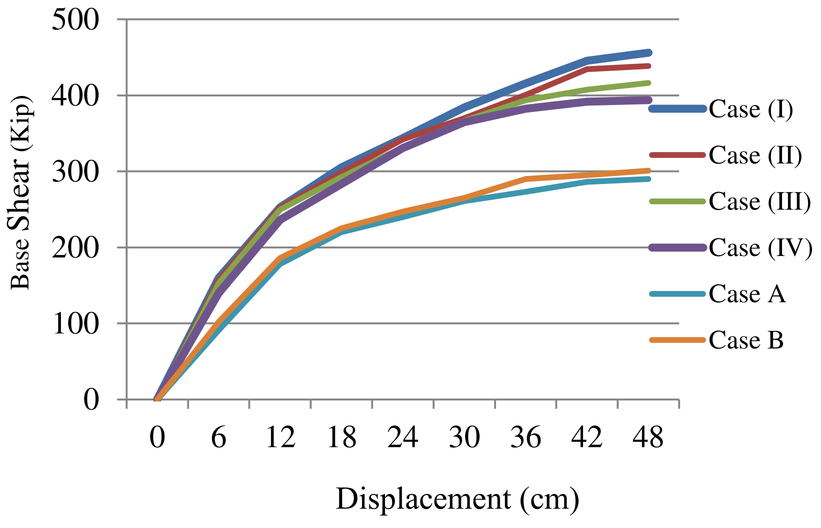

Figure 3: Capacity Curves of Cases (I, II, III, IV), Case (A) and Case (B)

3.2 Seismic Safety Analysis

First of all, the failure probability of the original building in DBE earthquake level is calculated by methodology described in above. The calculated values are shown in table (2) to (8) .The fragility curves are shown in figure (4). Then the failure probabilities of the damaged buildings for total six cases in DBE earthquake level are calculated and compared to the original building in figures (5).

Table 2: Estimation of failure probability of the original building

Spectral Acceleration (g)	SA+σ (g)	SA-σ (g)	Yield Displacement (cm)	Critical Displacement μ_{ucr} (cm)	Ductility	Period, T
0.5	0.525	0.475	13.1	35	2.672	1.117
0.55	0.5775	0.5225	13.1	35	2.672	1.207
0.6	0.63	0.57	13.1	35	2.672	1.297
0.65	0.6825	0.6175	13.1	35	2.672	1.351
0.7	0.735	0.665	13.1	35	2.672	1.412
0.75	0.7875	0.7125	13.1	35	2.672	1.424

Table 3: Estimation of failure probability of the original building

Surface Acceleration (g)	Maxi Roof Displacement , μ_u (cm)	u_1 (cm)	u_2 (cm)	σ_u	μ_{ucr} (cm)	Pf
0.2	19.87	21.855	17.881	1.987	35.000	0.000
0.22	25.52	28.070	22.966	2.552	35.000	0.000
0.24	32.14	35.359	28.930	3.214	35.000	0.187
0.26	37.78	41.561	34.005	3.778	35.000	0.769
0.28	44.45	48.891	40.002	4.445	35.000	0.983
0.3	48.43	53.278	43.591	4.843	35.000	0.997

Table 4: Estimation of failure probability of the damaged buildings for case (I)

Surface Acceleration(g)	μ_u (cm)	u_1 (cm)	u_2 (cm)	σ_u	μ_{ucr} (cm)	Pf
0.200	21.400	23.540	19.260	2.140	35.000	0.000
0.220	26.000	28.600	23.400	2.600	35.000	0.000
0.240	32.000	35.200	28.800	3.200	35.000	0.174
0.260	39.000	42.900	35.100	3.900	35.000	0.847
0.280	49.500	54.450	44.550	4.950	35.000	0.998
0.300	56.000	61.600	50.400	5.600	35.000	1.000

Table 5: Estimation of failure probability of the damaged buildings for case (II)

Surface Acceleration(g)	μ_u (cm)	u_1 (cm)	u_2 (cm)	σ_u	μ_{ucr} (cm)	Pf
0.200	22.100	24.310	19.890	2.210	35.000	0.000
0.220	28.000	30.800	25.200	2.800	35.000	0.006
0.240	33.300	36.630	29.970	3.330	35.000	0.305
0.260	41.000	45.100	36.900	4.100	35.000	0.886
0.280	50.000	55.000	45.000	5.000	35.000	0.999
0.300	56.500	62.150	50.850	5.650	35.000	1.000

Table 6: Estimation of failure probability of the damaged buildings for case (III)

Surface Acceleration(g)	μ_u (cm)	u_1 (cm)	u_2 (cm)	σ_u	μ_{ucr} (cm)	Pf
0.200	23.000	25.300	20.700	2.300	35.000	0.000
0.220	29.000	31.900	26.100	2.900	35.000	0.019
0.240	36.300	39.930	32.670	3.630	35.000	0.640
0.260	39.800	43.780	35.820	3.980	35.000	0.928
0.280	50.000	55.000	45.000	5.000	35.000	0.999
0.300	57.500	63.250	51.750	5.750	35.000	1.000

Table 7: Estimation of failure probability of the damaged buildings for case (IV)

Surface Acceleration(g)	μ_u (cm)	u_1 (cm)	u_2 (cm)	σ_u	μ_{ucr} (cm)	Pf
0.200	24.000	26.400	21.600	2.400	35.000	0.000
0.220	29.000	31.900	26.100	2.900	35.000	0.019
0.240	33.600	36.960	30.240	3.360	35.000	0.338
0.260	48.637	53.501	43.773	4.864	35.000	0.997
0.280	52.034	57.238	46.831	5.203	35.000	0.999
0.300	58.000	63.800	52.200	5.800	35.000	1.000

Table 8: Estimation of failure probability of the damaged buildings for case (A)

Surface Acceleration(g)	μ_u (cm)	u_1 (cm)	u_2 (cm)	σ_u	μ_{ucr} (cm)	Pf
0.200	30.000	33.000	27.000	3.000	35.000	0.048
0.220	35.000	38.500	31.500	3.500	35.000	0.500
0.240	40.000	44.000	36.000	4.000	35.000	0.894
0.260	43.000	47.300	38.700	4.300	35.000	0.969
0.280	45.000	49.500	40.500	4.500	35.000	0.987

Table 9.Estimation of failure probability of the damaged buildings for case (B)

Surface Acceleration(g)	μ_u (cm)	u_1 (cm)	u_2 (cm)	σ_u	μ_{ucr} (cm)	Pf
0.200	24.000	26.400	21.600	2.400	35.000	0.000
0.220	29.500	32.450	26.550	2.950	35.000	0.031
0.240	34.000	37.400	30.600	3.400	35.000	0.384
0.260	40.000	44.000	36.000	4.000	35.000	0.894
0.280	42.000	46.200	37.800	4.200	35.000	0.952

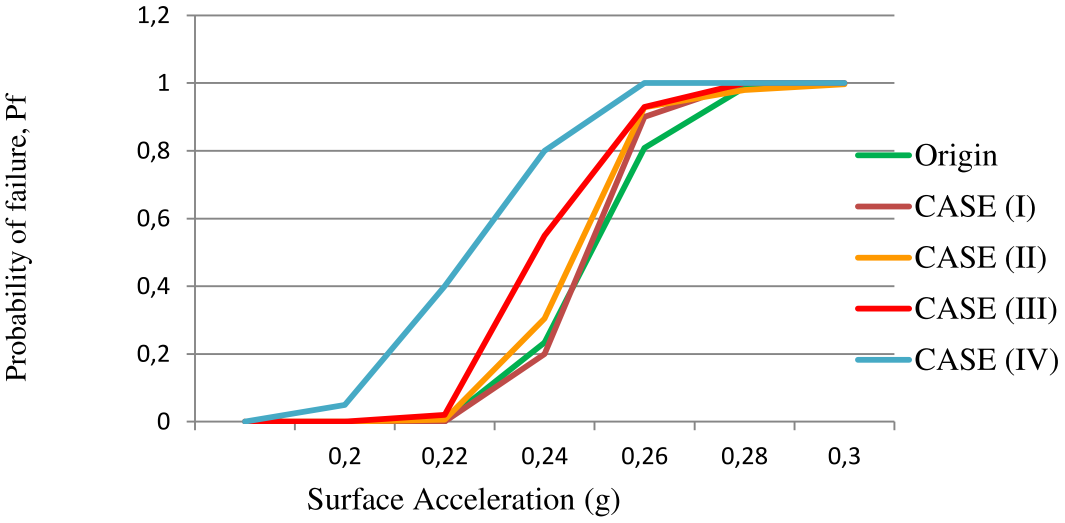

Figure 4.Failure probability of the original building and damaged buildings for cases (I, II, III, IV)

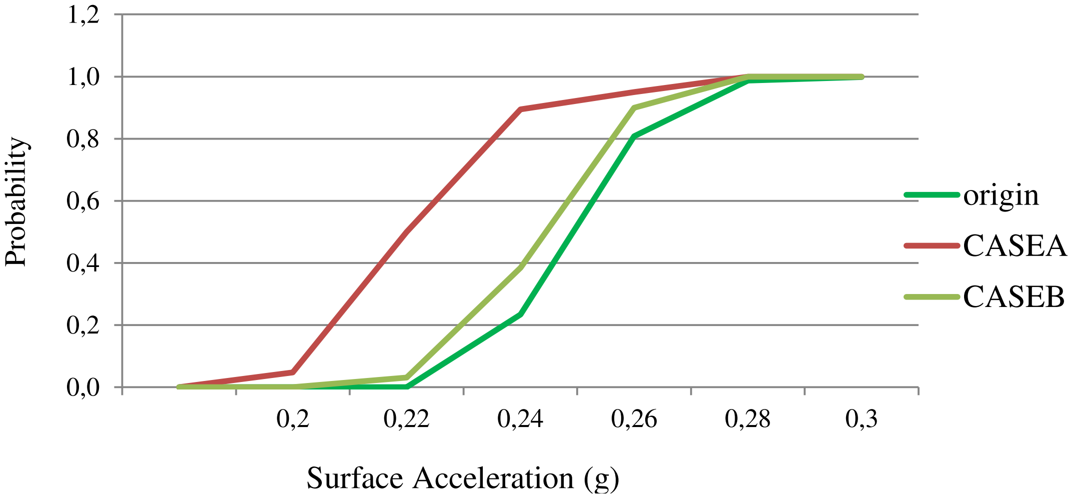

Figure 5.Failure probability of the original building and damaged buildings for cases (A and B)

3.3 Comparison of the seismic risks

The numerical condition for this simulation study is shown in Table (10). In the initial design, the seismic risk for life cycle is estimated by equation (6). In the stage of the repair or re-construction after the abnormal loadings, on the other hand, the seismic risk can be assessed by Equation (9).In this figure, CA/Co=1 means that the re-construction cost is equal to the initial one. But CA/Co=0.1 means that the repair cost is equal to the 10% of the initial cost.

For Case (I) and Case (II), figure (6) shows that the seismic risk for the case of CA/Co=1 (re-construction type) is smaller after the TA/T=0.4 than the initial risk. . It means that if the abnormal event occurred after 20years of construction, the seismic risk can be reduced smaller than that in the initial plan. The seismic risk for the case of CA/Co=1 (re-construction type) is higher than the initial plan during 20 years after construction (TA/T=0.1 to 0.4). If an abnormal event occurs during 5years of construction (TA/T=0.1), the building owner has the maximum risk and some measure such as the repair or re-construction should be taken immediately after the event.

For Case (III), figure (7) shows that the seismic risk for the case of CA/Co=1 (re-construction type) is smaller after the TA/T=0.5 than the initial risk. It means that if the abnormal event occurred later than in the half of the life cycle period of the building, the seismic risk can be reduced smaller than that in the initial plan. The seismic risk for the case of CA/Co=1 (re-construction type) is higher than the initial plan during 25years of construction (TA/T=0.1 to 0.5). The repair or re-construction should be taken immediately if an abnormal event occurs during 12 years of construction (TA/T=0.1 to 0.25).

For Case (IV) and Case (A), figure (8) shows that the seismic risk for the case of CA/Co=1 (re-construction type) is smaller after the TA/T=0.6 than the initial risk. . It means that if the abnormal event occurred after 30years of construction, the seismic risk can be reduced smaller than that in the initial plan. If an abnormal event occurs during 15years of construction (TA/T=0.1 to 0.3), the building owner has the maximum risk and some measure such as the repair or re-construction should be taken immediately after the event.

For Case (B), figure (9) shows that the seismic risk for the case of CA/Co=1 (re-construction type) is smaller after the TA/T=0.5 than the initial risk. It means that if the abnormal event occurred later than in the half of the life cycle period of the building, the seismic risk can be reduced smaller than that in the initial plan. If an abnormal event occurs during 10years of construction (TA/T=0.1 to 0.2), the building owner has the maximum risk and some measure such as the repair or re-construction should be taken immediately after the event.

Table 10.Numerical Simulation

Item	Symbol	Value
re-construction cost ratio	C_A/Co	1
repair cost ratio	C_A/Co	0.1
the whole period	T	50year
Abnormal load occurred	T_A	variable
Return period of an earthquake	T_R	475
maintenance cost ratio	C_M/Co	0.4
pf for the original building at 0.25g	p_f	0.5
pf for case (I) at 0.25g	p_f *	0.6
pf for case (II) at 0.25g	p_f *	0.6
pf for case (III) at 0.25g	p_f *	0.8
pf for case (IV) at 0.25g	p_f *	0.9
pf for case (A) at 0.25g	p_f *	0.9
pf for case (B) at 0.25g	p_f *	0.7

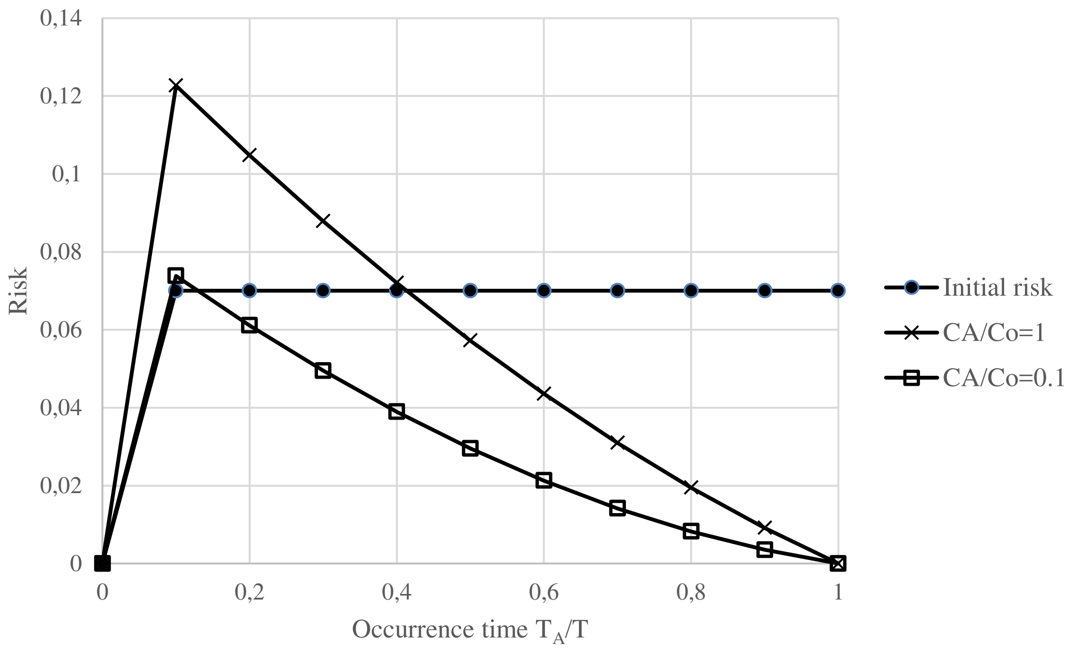

Figure 6. Seismic Risk Comparison for Case (I) and (II)

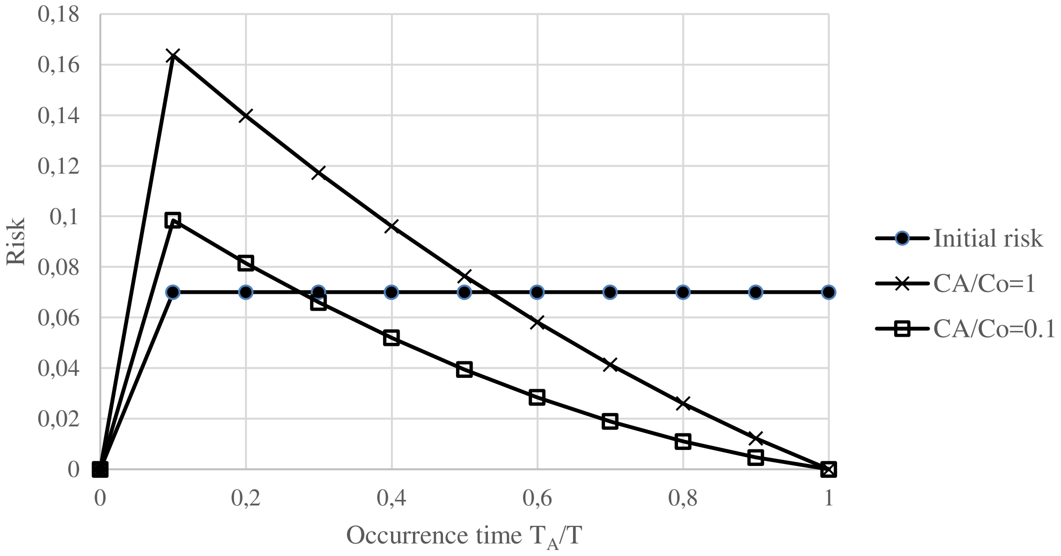

Figure 7. Seismic Risk Comparison for Case (III)

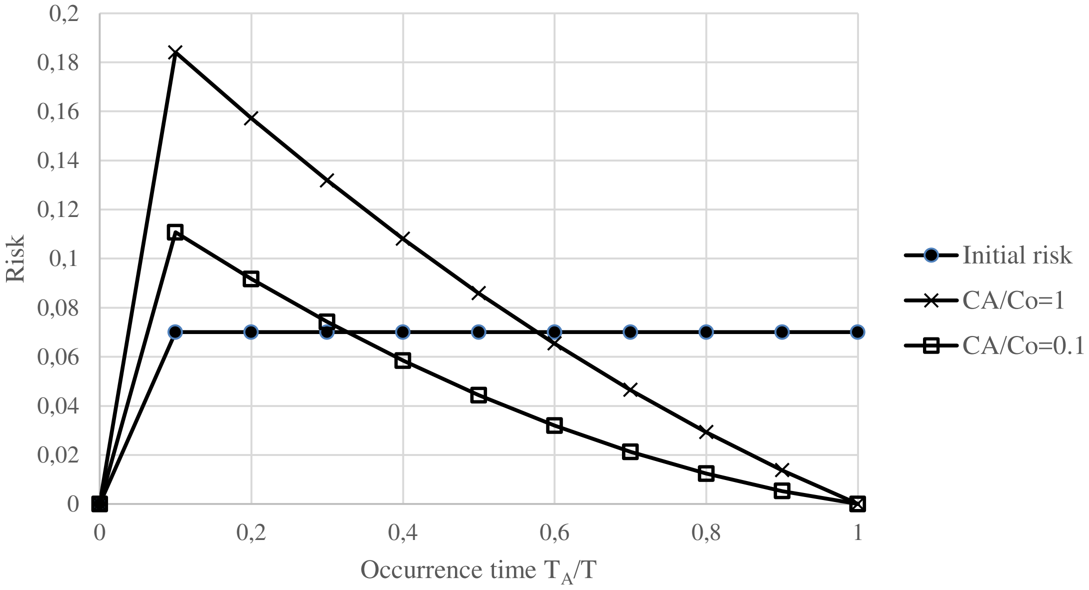

Figure 8. Seismic Risk Comparison for Case (IV) and Case (A)

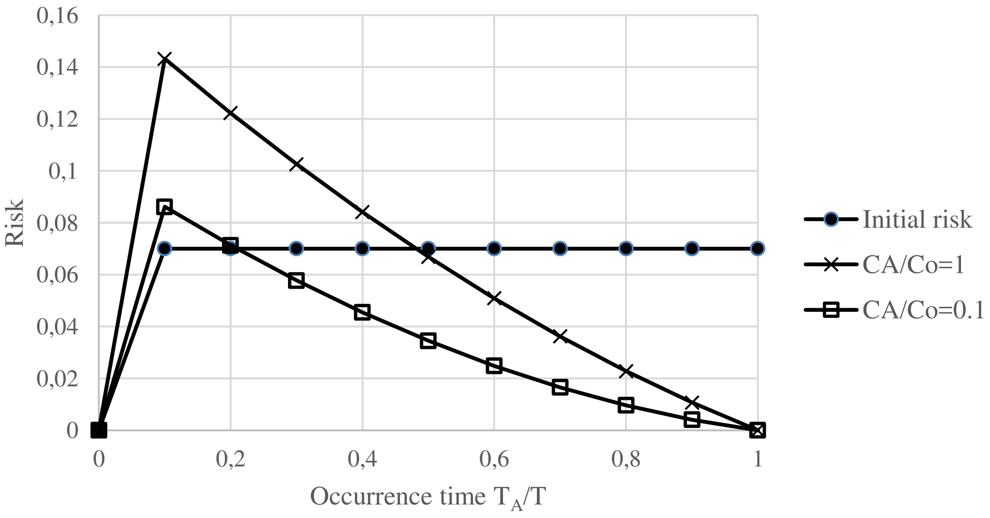

Figure 9. Seismic Risk Comparison for Case (B)

3.4 Economical restoration cost for the investment

Time that the abnormal load occurs affect the economical restoration cost and the benefits of the building at the end of the service life. Moreover, the maximum restoration cost can be estimated considering present worth value, future worth value and interest rate of money. The total floor area of the case study building is 482 square meter (5184 square feet) and present worth $99532. The expected benefit of the building is $11520 for a year and future worth value is $1919830 with the 8% interest rate of money for the normal case of no accident occurs after 50years. However, the restoration cost allowance is $88371 for the case of abnormal load occurred after 10years of construction, $190837 for the case of abnormal load occurred after 20years of construction, $411980 for the case of abnormal load occurred after 30years of construction, $888810 for the case of abnormal load occurred after 40years of construction to get the expected benefit amount of $1919830. It means that the building should be repaired if it is possible to control the risk or damage condition within the maximum restoration allowance. Otherwise, it would be more economical to reconstruct.

4. CONCLUSION:

The damaged building should be demolished if the risk of the damaged building is greater than that of a new building. A chance of re-use for damaged buildings by abnormal loading conditions is very limited. Moreover, potential damaged effect consideration is important for future seismic risk assessment. The methodology how to assess the safety of the buildings in the seismic environment after abnormal loadings has been presented and the period of time at which the accident abnormal load occurs in the service life affect the benefits and decisions for the structural investment. All in all, the residual building which is physically stable in appearance after an accident should be checked against natural hazard such as earthquake loading for public safety.

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