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Building specific damage estimation

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ABSTRACT : Earthquakes are a potential threat with serious economic losses. Several efforts are being made to estimate possible losses for future events. Many of the existing methods are empirical and are based on past history of losses. In this paper, an objective method of assessing monetary damage of a building based on structural response for a given earthquake motion is presented. The damage components are classified as structural, nonstructural and contents damage. Each component is related to a structural response parameter, which is obtained from nonlinear time history analysis. Structural damage for each member is assessed from an energy based damage index of the member. Nonstructural damage at each story level is assessed based on interstory drift and contents damage at each story level is assessed based on floor acceleration. Mapping from response damage index to monetary (dollar) damage index is done in a deterministic manner. The methodology is applied to a reinforced concrete moment resisting frame building.

1 INTRODUCTION

Earthquakes are a potential threat with serious economic losses and human suffering. Loma Prieta earthquake of october 17, 1989 in the Santa Cruz mountains of northern California has reminded us again about the consequences. The overall building performance was good with little to moderate building damage structurally. Compared to the property loss, the casualties were light (Benuska 1990). This indicates that we are able to design for life safety but we have not designed buildings for limiting monetary damage. The next objective logically should be to develop design strategies which can limit economic losses. To design to limit these losses, we need methodologies to predict or estimate losses from the expected structural response due to an earthquake. Previous work in this direction was from Czarnecki (1973), Hasselman et al. (1980) and Ferrito (1984).

Czarnecki (1973) used energy capacity of a member under monotonically increasing load and drift as response parameters for structural and nonstructural damage respectively. Under earthquake loads the energy capacity of a member is not unique(Uang and Bertero 1988) and hence we need to use a better damage model applicable to cyclic loading to model expected structural damage. Hasselman et al. (1980) used interstory drift to model both structural and nonstructural damage. Ferrito (1984) used interstory drift as response parameter for structural damage and both interstory drift and floor acceleration as response parameters for nonstructural and contents damage.

This paper presents an integrated methodolgy for monetary damage estimation of reinforced concrete structures based on structural response, by considering response at the member level. The monetary damage is referred to as $-damage in further discussion. Damage model for generic building is presented first and the response parameters for damage of components are discussed. Next the general mapping from response to $-damage is discussed and actual response damage index to $-damage index mapping functions for different components of building damage are presented. An example is presented to illustrate the methodolgy. The program Inelastic Dynamic Analysis of Reinforced Concrete Structures - IDARC (Park et al. 1987) is used to obtain the nonlinear response of the building. The scope of the paper is limited to ductile moment resisting frames.

2 DAMAGE MODEL

Economic loss of a building due to an earthquake generally includes the monetary value of the direct physical $-damage to the building and the commercial loss due to down-time for the building repairs. The loss due to down-time for the building depends on the direct physical damage and the type of usage of the building and may constitute more towards overall economic loss than any other single factor. However, the discussion in this paper is restricted to direct physical $-damage of the building only. The building damage model and its components are shown in Fig.1. The response parameters .for damage indication of different components are also shown in Fig.1. The building damage is thus madeup of structural, nonstructural and contents damage. Nonstructural damage is comprised of architectural damage and mechanical, electrical and plumbing (MEP) damage. From the literature, the following parameters have been identified to represent the damage of various components

2.1 *Structural damage*

Structural damage is damage of columns, beams,

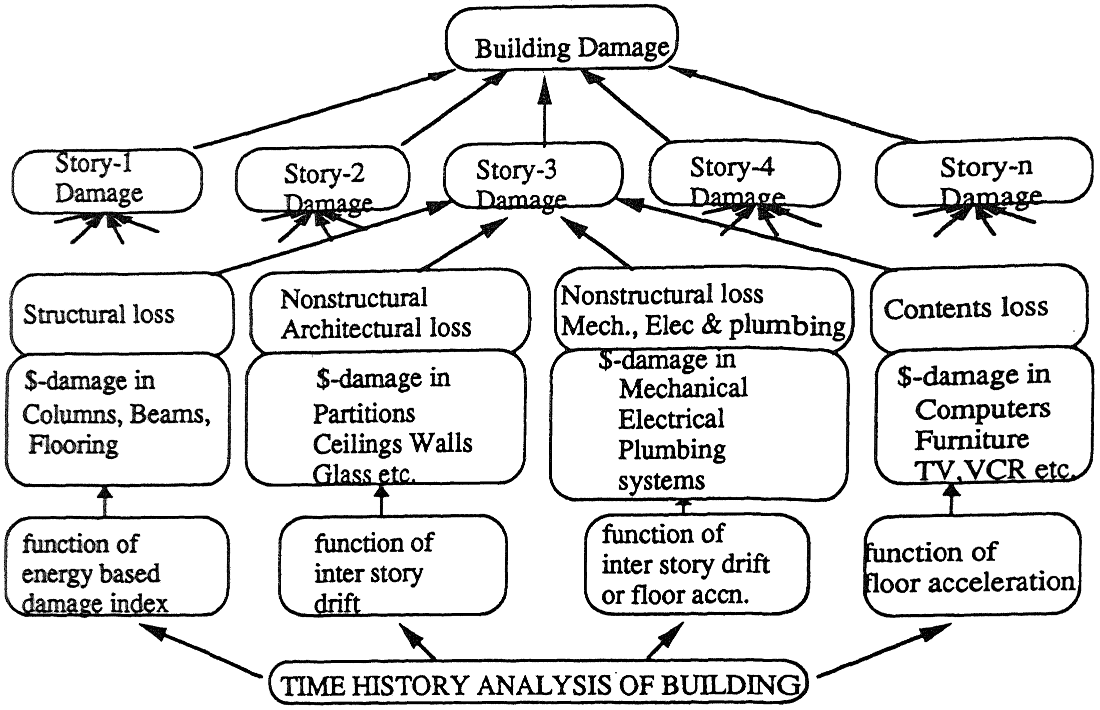

Figure 1. Building damage model

flooring system and shear walls. Park and Ang's (1985) damage index for reinforced concrete members is adopted to assess structural damage of individual member. It is based on the idea that damage in a member is dependent on both the maximum deformation level and the hysteretic energy absorbed by the member. Thus this damage index considers the cumulative damage due to cyclic loading. The Damage Index, D, of a member is defined as

$$D = \frac{\delta_m}{\delta_u} + \beta \frac{\int dE}{P_y \, \delta_u} \qquad (1)$$

where

δ_m = Maximum deformation experienced by member during cyclic loading

δ_u = Ultimate deformation of member under monotonic loading

β = Strength deterioration parameter due to cyclic loading

P_y = Yield strength of the member

$\int dE$ = Cumulative hysteretic energy absorbed

2.2 *Nonstructural damage*

2.2.1 *Architectural damage*

Many investigators have studied correlations between architectural damage (nonstructural) and interstory drift ratio. It is widely accepted (Czarnecki 1973, Hasselman et al. 1980, and Ferrito 1985) that architectural damage is generally well correlated to interstory drift. The building codes also follow limits on drift ratio to reduce architectural damage. Hence, interstory drift is adopted as response damage indicator for architectural damage.

2.2.2 *Mechanical, electrical, and plumbing damage (MEP damage)*

Mechanical, electrical, and plumbing damage depends on the interstory drift and also on the floor acceleration depending on the type of subcomponents involved for the specific building. For example, elevator mechanical room equipment damage may depend on the acceleration level. However, for the purpose of this paper, MEP damage is also assumed to be related to interstory drift.

2.3 *Contents damage*

Contents damage covers damage at any floor level to computers, valuable items, books in libraries, furniture etc. It is very difficult to predict this type of damage but an attempt can be made. The response factor which can be associated with contents damage is the floor acceleration, as it is the acceleration which cauases things to be thrown around. The damage here may mean the amount of money one has to spend to get the contents back into pre-earthquake condition even if there are no actual repairs.

2.4 *Global damage*

After defining the response factors, the next step is to assess the damage each component has suffered due to a given earthquake. This is obtained by performing a nonlinear analysis of the structure for the earthquake motion. The program IDARC - Inelastic Dynamic Analysis of Reinforced Concrete Frame and Shear Wall Buildings (Park et al. 1987) - is used to obtain the structural response. The response damage index of each member, the maximum interstory drift at each story and the maximum acceleration felt at each story are now available from analysis. In general, any response damage in a component is associated with a corresponding dollar damage index for that component which is defined as "repair cost /replacement cost" for the component. The response damage is thus converted to dollar damage index for each component using the mapping presented in the next section. The structural, architectural, MEP and contents \$-damages are estimated at each story based on the maximum responses experienced at each story.

2.4.1 *Cost weighting*

Now that the individual dollar damage indices are available for each component, we can combine them to arrive at global damage factor for the structure. It is common practise to combine the individual components by some weighting factors. Park et al.(1985a) used energy weighting to obtain global damage index. Bracci et al.(1989) used tributary gravity load of component as weighting factor. The global damage index, in general, is given by

$$\text{Global Damage Index} = \frac{\sum_{1}^{n} w_i{*}D_i}{\sum_{1}^{n} w_i} \qquad (2)$$

where
w_i = weighting factor for the component i,
D_i = \$-damage index for the component i,
n = number of components

As we are interested in assessing dollar damage, it is proposed to use cost of the components as weighting factors. The cost weighting has a physical significance as the product $w_i{*}D_i$ represents the repair cost or dollar damage for the component as w_i represents the replacement cost of the component and D_i represents the dollar damage index. And also, the summation $\sum_{1}^{n} w_i{*}D_i$ represents the total repair cost and $\sum_{1}^{n} w_i$ represents the total replacement cost. As the building costs and damages have been divided into different components viz. structural, architectural, MEP, contents and miscellaneous, the global damage indices can be generated for each of them and also for the combined total cost. The same procedure is also used to generate story level damage indices.

3 MAPPING FROM RESPONSE TO \$-DAMAGE

It is convenient to represent response in terms of response index and \$-damage in terms of \$-damage index. Response damage index is the ratio of maximum response experienced by the component to the response capacity of the component. \$-damage index is the ratio of repair cost to replacement cost of the component under consideration. These indices vary from zero(0) to one(1). As the response damage index increases from 0 to 1, the \$-damage index may vary from 0 to 1(some times more than 1). Any response damage index can be converted into \$-damage index using either deterministic (crisp) mapping or interval mapping or probabilistic mapping or fuzzy mapping. The mapping method adopted depends on the type of information available. Only the deterministic mapping is presented in this paper.

Czarnecki (1973) proposed and applied a mapping for the structural damage models. If an element absorbs an amount of inelastic energy, A_x, then a certain fraction of total inelastic energy absorption capacity of the element, A, has been dissipated. To restore the structure to its original condition, a certain amount of money must be spent to repair or replace the structural elements. As energy absorbed, A_x, becomes larger and approaches the energy capacity, A, the amount of money spent to repair the structure becomes a greater fraction of its initial value. The relation proposed by Czarnecki is as follows:

$$D = \left|\frac{A_x}{A}\right|^n \qquad (3)$$

where

$$D = \frac{\text{damage to a structural element}}{\text{value of structural element}}$$

The ratio, $\frac{A_x}{A}$, represents the response based damage index and D represents the \$-damage index. A more general variation was suggested by Powell and Allahabadi (1988) with a provision that up to certain response damage index level the \$-damage index is zero. This type of data is generally not available for building components because of the complexity and the nature of the problem. However, three approaches are presented below with different assumptions to generate such data.

3.1 *Absence of data*

In the absence of any specific data relating response damage index to \$-damage index, it may be reasonable to assume

$$\text{\$-damage index} = \text{response damage index} \qquad (4)$$

This mapping gives high \$-damage values in the low response damage index region resulting in overestimation of \$-damage. This is shown in Fig.2.

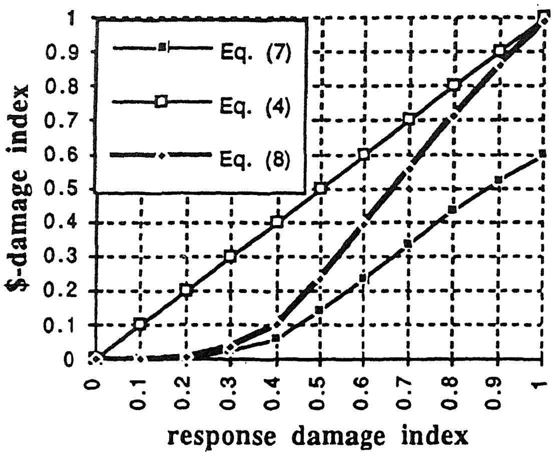

Figure 2. Response damage index .vs. $-damage index (general)

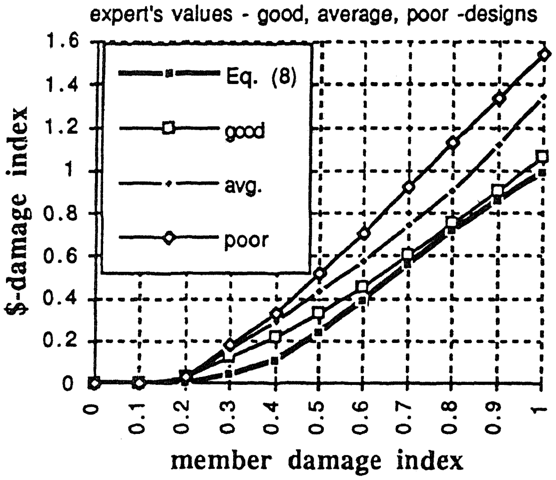

Figure 3. Response damage index .vs. $-damage index (structural damage)

3.2 *From component test data*

Statistical information is available on the energy based damage index and failure of components for structural damage. Park and Ang (1985) presented correlation between their damage index for structural damage of reinforced concrete members and their failure. The damage index has a lognormal distribution with a mean value of 1.008 at failure for 403 samples and a standard deviation of 0.535. Though the data for $-damage is not available, the failure correlation data can be used to generate data for mapping response damage index to $-damage index as follows.

For lognormal distribution we have the following parameters:

$\zeta = 0.535/1.0 \quad = 53\ \%$

$\lambda = \ln 1.008\ -\ 0.5\ \zeta^2 = -0.1325$

The probability that the member fails, when response damage index is d, is given by

$$p(\text{failure/resp. damage ind.}=d) = \phi\left(\frac{\ln d + 0.1325}{0.53}\right) \quad (5)$$

If p(failure) = 0 then $-loss = 0.
If p(failure) = 1 then $-loss = replacement cost.
Assuming for simplicity that a member has only two states (no failure and failure), the expected $-loss can be obtained as

$-loss = p(failure) * replacement cost (6)
Hence $-damage index = $-loss/replacement cost
= p(failure)

$$= \phi\left(\frac{\ln d + 0.1325}{0.53}\right) \quad (7)$$

The $-damage index values for different response damage index values are presented in Fig. 2 based on eq.(7). It may be seen that the $-damage is zero till about a response damage index of 0.2. But the $-damage index at response damage index of 1.0 is only about 0.6. This appears to be low from practical point. Intuitively the $-damage index should be 1.0 or more when the component is fully damaged. Hence, to make $-damage index equal to 1.0 when the response damage index is 1.0, it is suggested to scale the values of Eq.7 by 1.65 (~1/0.6). This is shown in Fig.2, which can be used as a mapping function from response damage index to $-damage index.
$-damage index = equation (7) * 1.65 (8)

3.3 *From Expert's Knowledge*

The third approach to generate such data is based on experts' opinions. Data from 2 experts in the field was collected to generate the required mapping functions. This is discussed in the next section. However, the experts made it clear that the data is not available in this form and it is difficult to obtain such information and the values they provided are from what they felt reasonable.

4 ACTUAL COMPONENT RESPONSE TO $-DAMAGE MAPPING

4.1 *Structural $-damage*

To develop mapping function from response damage index to $-damage one needs behavioral information on physical state of the component. Based on the experimental observations (Bracci et al. 1989, Hatamoto et al. 1990), it is reasonable to assume that in the low end of response damage index (0 - 0.3), when the damage is minor, usually no repairs are needed. In the intermediate range of response damage index (0.3 - 0.6), repairs need to be carried out. In the irreparable range of damage index (0.6 - 1.0) the $-damage index would be of the order of 1.0. The eq.(8) which follows this trend can be used as a mapping function from response damage index to structural $-damage index at member level.

The estimates from experts for structural damage are very close and their average values are shown in Fig.3. It is felt that quality of conceptual design plays an important role in resisting earthquake forces. A building with good conceptual design will suffer less damage. This attribute will account for any irregularities in design not accounted for in analysis and the experts may classify the design as good, average or poor. The estimates from experts are presented for all the three qualities of design . It may be seen that eq.(8) comes close to experts values for good quality design.

4.2 *Architectural $-damage (Nonstructural)*

It is generally considered that beyond a drift ratio of 0.02 architectural $-damage is 100% (Czarnecki 1973, Hasselman 1980, Ferrito 1984). Freeman (1977) presented racking tests results on partition walls which indicated an interstory drift ratio of 0.017 at failure stage. Freeman (1985) also recommends a maximum drift ratio limit of 0.005 (minor damage) at the working level and a limit of 0.015 for response during a major earthquake as reasonable goals. Wang (1987) reported cladding performance on a full scale test frame which indicated cladding failure at an interstory drift ratio of 0.025. Based on these reports, it is felt reasonable that beyond an interstory drift value of 0.02, the architectural damage may be assumed to be 100%.

With a maximum threshold value of 0.02 (response damage index = 1) for interstory drift, the general $-damage index mapping is transformed to drift related $-damage mapping for architectural damage (Fig.4). Eq.(8) appears to model well the low end of drift. No $-damage is expected up to drift of about 0.004, which is reasonable to expect and tallies with the code limitation of drift for working loads.

The estimates from experts for architectural damage are also presented in Fig. 4 for all the three qualities of design . Because of the experimental values of failure of partition walls and cladding at about a drift value of 0.02, we may adopt eq. (8) for evaluation.

4.3 *MEP$-damage (Nonstructural)*

MEP damage may depend on interstory drift and/or floor acceleration. The expert estimates obtained from the two experts are very different indicating difficulty in generating such data. For the present it is assumed to be dependent on interstory drift and the same mapping as for architectural damage in Fig.4 is used.

4.4 *Contents $-damage*

It is reasonable to assume that contents $-damage is related to floor acceleration. An acceleration value of 1.4g is suggested by Ferrito (1984) beyond which the damage is 100% (for conventional structures and their contents). Using this value as maximum threshold accn. (response damage index = 1), the general $-damage index mapping is transformed to acceleration related $-damage index mapping for contents as in Fig. 5 (Eq.8).

One factor which needs to be incorporated is the degree of protection provided for contents(Well protected, averagely protected, poorly protected). The $-damage index should vary depending on the level of protection.

Another attribute that is raised by experts is the quality of contents viz. sensitive and nonsensitive contents. Sensitive contents are those that are sensitive to acceleration levels like computers etc. whose repair costs may be high. Nonsensitive contents are those like office furniture etc. for which repair costs are less. These (subjective) mapping relations provided by the experts are shown in Fig.5 for average level of protection.

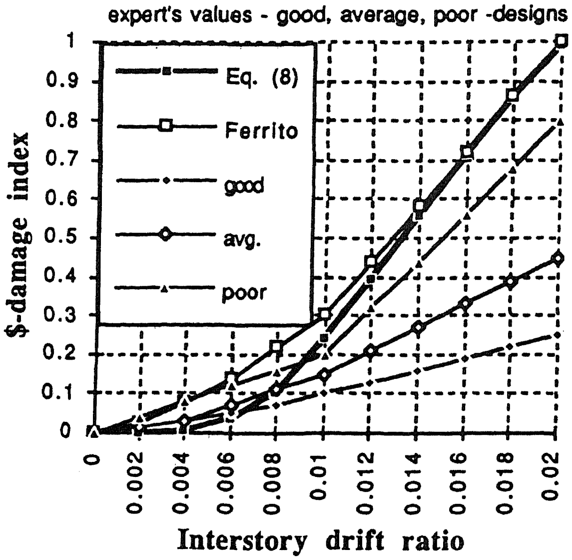

Figure 4. Interstory drift .vs. $-damage index (architectural damage)

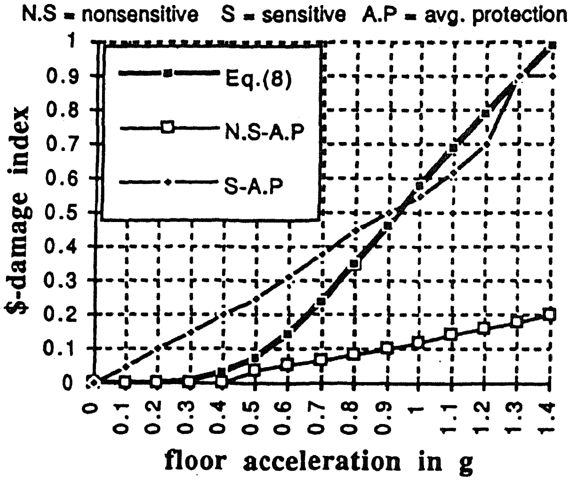

Figure 5. Floor acceleration .vs. $-damage index (contents damage)

5 EXAMPLE

The Holiday Inn located on Orion street in Van Nuys suffered considerable non-structural damage during 1971 San Fernando earthquake(Murphy 1973). Structural damage was reported to be slight. This building is a 7-story by 3-bay concrete ductile moment-resisting frame with flat slab. The response is obtained using IDARC program. For reinforced concrete structures, a damping ratio of 5% is generally acceptable and hence the same is used in the analysis. The structural members' costs are based on "Means concrete cost data 1988" (Means). The architectural and MEP costs are obtained from the structural cost based on the assumed distribution of building costs (Structural 27%, Architectural 25%, MEP 30%, Miscellaneous 18%), which are typical for reinforced concrete buildings of this type . The actual cost figures may be used, if they are available. The $-damage at each story is obtained based on the models presented above for structural damage, architectural damage, mechanical, electrical and plumbing damage, and contents damage. The global $-damage summary is presented in Table-1 in terms of $-damage index. The damage indices are obtained by using eq.(8) and also the mapping suggested by experts for average quality of design. The model predictions are close to the reported damages. The story-wise damage distribution is given in Table-2 based on eq.(8). The actual nonstructural damage was reported(Murphy 1973) to be severe in second and third floors and least in sixth and seventh floors. The results presented in Table-2 also indicate maximum damage in second,third and fourth floors and least damage in seventh floor which may be observed from cost-damage indices for nonstructural damage. It is interesting to observe from Tables-1 and 2 that for about 10% total damage in the building, the damage is mainly in the nonstructural items and structural damage is insignificant. The weighted nonstructural damage for the building is about 18% of the cost of nonstructural items and may go up to about 30% - 40% at certain floors depending on the type of earthquake motion and structural response.The proposed method appears to model the damage observations closely and may become a useful tool for damage prediction.

Table 1. $-damage Index as % of building cost for Holiday Inn (PGA : 0.25g -Transverse direction)

Damage Component	(Eq.8)	Experts' mapping *	Reported (Murphy)
Structural	0.16	0.74	0.15
Nonstruc.	9.6	7.0	11.0
Misc.	0.1	0.5	N/A
Total	9.9	8.2	11.15
Contents **	0	9.5	N/A

* Experts' mapping for average design quality
** % of contents value only N/A - not available

Table 2. Damage distribution for Holiday Inn [based on (Eq.8)](PGA : 0.25g -Transverse direction)

	Structural	Architectural &MEP	
Story	Cost-damage index (weighted from member level)	Interstory drift ratio	Cost-damage index
1	0.011	0.007	0.066
2	0.015	0.011	0.324
3	0.013	0.012	0.374
4	0	0.010	0.260
5	0	0.0082	0.115
6	0	0.0077	0.084
7	0	0.005	0
Total	0.006	Weighted	0.175

6 CONCLUSIONS

A methodolgy is presented for building specific monetary damage estimation based on expected structural response for a given earthquake. Different mapping functions are presented for mapping response damage index to monetary damage index for various components of damage. The mapping models can be refined based on more case studies of damaged buildings.

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