Damage as a measure of seismic resistance of masonry structures

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ABSTRACT

Experiments and earthquake damage observations indicate that physical damage to masonry walls and buildings is closely correlated with limit states, which determine the seismic resistance. It is therefore proposed that typical observed degree of damage to masonry structures be used as one of the possible reference points for the correlation of lateral resistance, ductility and energy dissipation capacity for different masonry structural types. The results of experimental investigations, carried out in the last decade, have been used to evaluate this correlation.

INTRODUCTION

Three characteristic limit states are usually defined on the lateral resistance-displacement curve, which is considered as the basic indicator of the seismic resistance of masonry walls and buildings. Namely, elastic limit, maximum resistance, and ultimate limit state. Quantification of lateral resistance, including all values of parameters which determine the limit states, is the matter of calculations: in order to obtain reliable information, adequate mathematical models and experimentally determined input parameters should be used. It is not possible to quantify the limit states on the basis of the observed damage, occurred to the walls and/or whole buildings. However, it has been found that, qualitatively, limit states can be also determined by the occurred damage.

Correlation between physical damage and seismic resistance is needed in the case where the usability of masonry buildings, damaged by earthquakes, needs to be evaluated. On the basis of the known relationships between the observed damage and seismic resistance, the remaining resistance of the building under consideration can be estimated and the chances that the building, already damaged by an earthquake, will survive an aftershock and/or repeated earthquake of the same intensity, can be assessed.

In this paper, an attempt has been made to determine the correlation between the limit states and damage to masonry walls and buildings. The results of experimental research in seismic behavior of masonry walls and models of masonry buildings, carried out at Slovenian National Building and Civil Engineering Institute (ZAG) in Ljubljana, have been used to carry out the correlation.

SEISMIC RESISTANCE AND LIMIT STATES

The seismic resistance of structural walls and whole masonry structures can be determined by a resistance envelope, which determines the relationship between the lateral resistance and deformation (rotation angle) of the wall or structural system. On the basis of the resistance envelope, the characteristic limit states can be defined and the regions specified, which determine the usability of buildings, with boundaries between the regions defined by the limit states. Namely, the region where the building is still usable, the region where the building is no more usable, but is still safe, and the region where there is a serious danger of collapse (Figure 1).

The following characteristic limit states are usually defined on the resistance envelope:

- elastic limit, where the first significant damage occurs to the structural system, with evident changes in stiffness,
- maximum resistance, and
- ultimate state, where the resistance of the system deteriorates below the acceptable limit. In practical seismic verification cases, degradation below 80% of maximum resistance is usually defined as the collapse of the building.

In a normal design practice, maximum resistance and elastic stiffness of individual walls are calculated on the basis of equations, which take into account the assumptions of the theory of elasticity. The parameters of resistance envelope at each respective limit state are then calculated as a function of these two basic parameters and empirically obtained correlations (Tomaževič, 1997).

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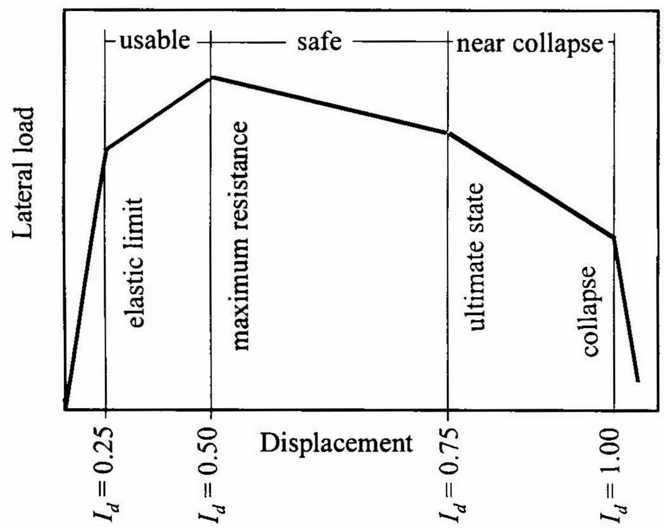

Figure 1. Seismic resistance envelope with characteristic limit states,
states of usability of building, and attributed damage indexes

In Figure 1, the limit states on the resistance envelope are defined by the resistance H and displacement d values at the elastic limit (H_e, d_e), at maximum resistance (H_{max}, d_{Hmax}), and at ultimate state (H_{du}, d_u). Since the displacement at maximum resistance is relatively small, the damage occurred to structural walls is not severe. Therefore, the building can be considered usable up until the maximum resistance is attained. Between maximum resistance and ultimate state, the damage to structural elements is severe, but can be repaired. The building is considered safe, but is no more usable. The real structure does not collapse at the so defined ultimate state. In most cases, the structure is able to exhibit additional displacements. However, although the actual collapse takes place at lateral displacement d_{max}, the structure is damaged beyond repair after exceeding the displacement at ultimate limit d_u.

DAMAGE AS A MEASURE OF SEISMIC RESISTANCE

On the basis of the analysis of the results of experimental research in seismic behavior of masonry walls and models of buildings, an attempt has been made to determine the correlation between the limit states and the extent of damage occurred to masonry walls and structural systems at each limit state.

Definition of damage index

Although the type of damage to masonry walls and buildings varies in dependence on construction system, such as plain masonry, confined masonry, and reinforced masonry, damage to structural walls can be classified and damage indexes defined in a uniform way. In order to find the correlation between the damage and lateral resistance, ductility, stiffness degradation, and energy dissipation capacity of different types of walls and structural systems, four distinct degrees of damage observed during cyclic lateral resistance tests of masonry walls and shaking table tests of models of masonry buildings have been distinguished and corresponding damage indexes I_d defined (damage index $I_d = 0$ means no damage). In the particular case discussed, damage indexes are correlated with the degree of physical damage: no other parameters, such as energy dissipation capacity and ductility, have been taken into account when defining the damage index.

In the case of prevailing shear behavior of structural walls, the description of typical damage patterns at characteristic limit states with attributed damaged indexes, is given as follows. A definition of damage indexes in the case of confined masonry walls is presented in Figure 2. For comparison, the resistance envelope curve, where the respective limit states are indicated, is shown in Figure 3.

- $I_d = 0.25$: the formation of first diagonally oriented cracks in the middle part of walls, passing through horizontal and vertical mortar joints. Elastic (crack) limit is attained at this damage level.
- $I_d = 0.50$: increased number of cracks with limited width, oriented diagonally in both diagonal directions. Maximum lateral resistance of the panel is attained at this damage level.

- $I_d = 0.75$: heavy damage. Increased number of wide diagonally oriented cracks. Crushing of individual masonry units. Strength degradation attains the acceptable level (80-70 % of maximum value). Ultimate state, as defined by the classification of limit states, is attained at this damage level.
- $I_d = 1.00$: increased width of cracks, crushing of units along both wall diagonals. Rupture or buckling of reinforcing bars (if reinforced). Severe strength degradation and final collapse.

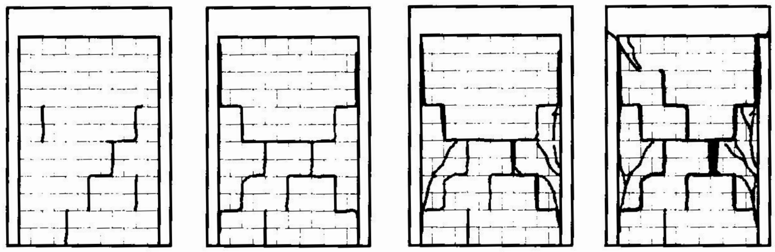

Figure 2. Definition of damage indexes I_d in the case of confined masonry walls

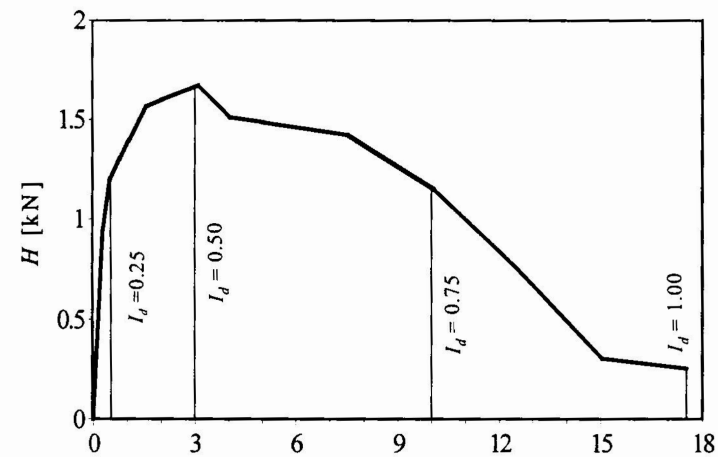

Figure 3. Lateral load - deformation curve for the case of confined masonry walls.
Damage indexes I_d are indicated at corresponding displacement amplitudes

Similar correlation between the observed damage, attributed damaged indexes and limit states has been considered in the case of the tested model buildings:

- $I_d = 0.25$: first major damage to structural walls, which may cause noticeable decay of the first natural vibration frequency of the building. Elastic (crack) limit.
- $I_d = 0.50$: increased number of cracks, typical for the governing behavior mechanism of individual walls (diagonal cracks in the case of shear, horizontal tension cracks in the case of flexural mechanism). As in the case of individual walls, this type of crack pattern is observed at the attained maximum lateral resistance of the building.
- $I_d = 0.75$: Heavy damage to the walls, defined by crushing at the corners of the building, falling out of parts of the walls, and/or crushing of individual masonry units. As in the case of individual structural walls, strength degradation of the structural system attains the acceptable level (80-70 % of maximum value). Ultimate state, as defined by the classification of limit states, is attained at this damage level.
- $I_d = 1.00$: Increased damage to the walls. Damage to horizontal structural elements, such as slabs and bond beams, crushing of concrete and rupture or buckling of reinforcing bars (if reinforced). Final collapse.

The definition of damage indexes in the case of a confined masonry building model is shown in Figure 4.

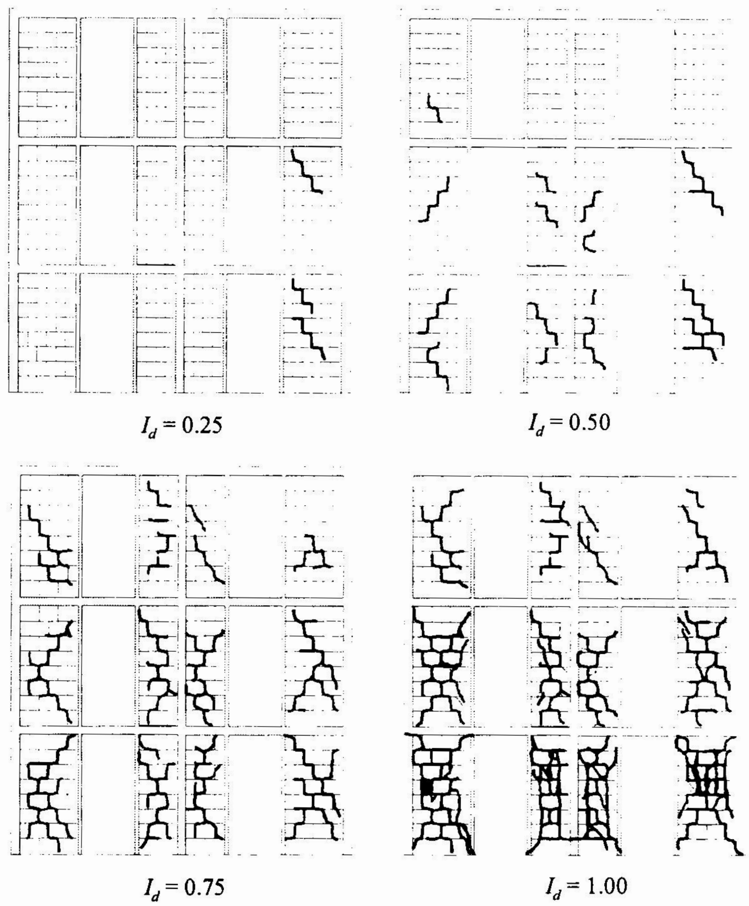

Figure 4. Definition of damage indexes I_d in the case of a confined masonry building model

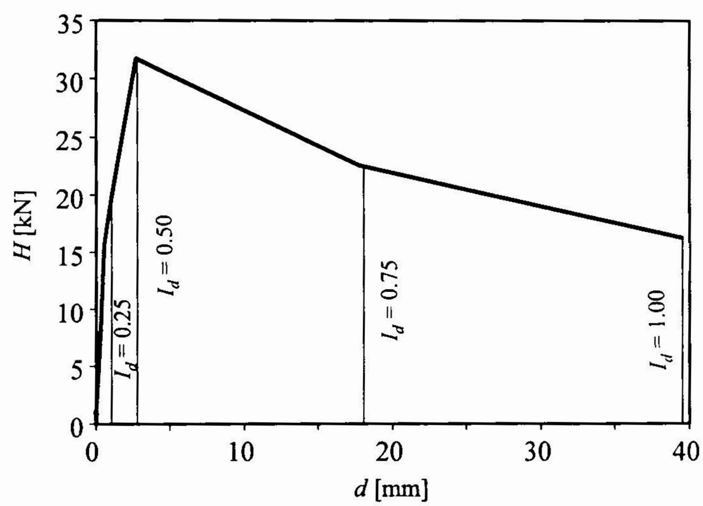

Figure 5. Lateral load - deformation curve for the case of a confined masonry building model. Damage indexes I_d are indicated at corresponding displacement amplitudes

Correlation between damage and parameters of seismic resistance

Whereas lateral resistance and ductility represent the main parameters of seismic resistance, strength and stiffness degradation, and energy dissipation capacity also influence the seismic behavior. To find the correlation between the observed damage level, expressed in terms of damage indexes I_d, and these parameters, the results of cyclic lateral resistance tests of masonry walls and shaking table tests of masonry building models (Tomaževič et al., 1990, Tomaževič and Lutman, 1993, Tomaževič and Klemenc, 1997) have been analyzed. Typical results obtained in the case of the tested series of confined and reinforced masonry walls are given in Tables 1 and 2, respectively. The following parameters have been correlated:

- R/R_{max} - ratio between resistance R at characteristic damage level and maximum lateral resistance R_{max},
- d/d_{max} - ratio between lateral displacement d at characteristic damage level and maximum displacement d_{max},
- K/K_e - ratio between secant stiffness K at characteristic damage level and effective, elastic stiffness of the wall K_e,
- E_{dis}/E_{inp} - ratio between dissipated, hysteretic energy E_{dis}, and input energy E_{inp}.

When analyzing the results presented in Tables 1 and 2, a correlation between the degree of damage to the walls, determined by damage index I_d, and limit states, which characterize the seismic resistance of the walls, can be seen. The correlation, however, depends on the type of masonry construction. Whereas similar relationships between the observed damage and stiffness degradation parameter have been obtained for both, confined and reinforced masonry walls, the relationships are somewhat different in the case of resistance, displacements and energy dissipation capacity, assessed at the same damage level.

Table 1. Correlation between damage index I_d and parameters of seismic resistance for the tested confined masonry walls

I_d	Limit state	Confined masonry walls			
		R/R_{max}	d/d_{max}	K/K_e	E_{dis}/E_{inp}
0.25	Elastic limit	0.43	0.04	1.00	0.50
0.50	Maximum resistance	1.00	0.21	0.36	0.37
0.75	Ultimate state	0.75	0.53	0.10	0.44
1.00	Collapse	0.30	1.00	0.02	0.53

Table 2. Correlation between damage index I_d and parameters of seismic resistance for the tested reinforced masonry walls

I_d	Limit state	Reinforced masonry walls			
		R/R_{max}	d/d_{max}	K/K_e	E_{dis}/E_{inp}
0.25	Elastic limit	0.88	0.19	1.00	0.56
0.50	Maximum resistance	1.00	0.59	0.38	0.59
0.75	Ultimate state	0.91	0.84	0.20	0.63
1.00	Collapse	0.66	1.00	0.11	0.72

The observed correlation between the damage and parameters which define the resistance envelope, can be used to develop simple empirical equations, by means of which the idealized resistance envelope can be determined. In most practical cases, the coefficients in the equations are determined on the basis of statistical evaluation of the observed relationships, and the calculated physical quantity is expressed as a function of damage index and initial value of the parameter under consideration.

Similar analysis as in the case of single masonry walls has been also carried out for the tested masonry building models. Typical results are presented in Tables 3 and 4 for reinforced and confined masonry building models, respectively. By correlating the values, calculated for each respective type of masonry in Tables 1-4, similar trends in changes of the values of the analyzed parameters can be seen in the case of both, individual walls and whole structures, belonging to the same type of masonry construction.

Table 3. Correlation between damage index I_d and parameters of seismic resistance for the tested confined masonry building model

I_d	Limit state	Confined masonry building			
		R/R_{max}	d/d_{max}	K/K_e	E_{dis}/E_{inp}
0.25	Elastic limit	0.49	0.02	1.00	0.21
0.50	Maximum resistance	1.00	0.11	0.43	0.23
0.75	Ultimate state	0.71	0.47	0.05	0.41
1.00	Collapse	0.52	1.00	0.02	0.40

Table 4. Correlation between damage index I_d and parameters of seismic resistance for the tested reinforced masonry building model (values evaluated with reference to ultimate limit state)

I_d	Limit state	Reinforced masonry building			
		R/R_{max}	d/d_{max}	K/K_e	E_{dis}/E_{inp}
0.25	Elastic limit	0.76	0.11	1.00	0.32
0.50	Maximum resistance	1.00	0.44	0.22	0.79
0.75	Ultimate state	0.82	1.00	0.22	0.92
1.00	Collapse	-	-	-	-

CONCLUSIONS

Damage occurred to masonry walls and buildings when subjected to seismic loads has been correlated with the parameters of seismic resistance. The analysis of results of cyclic lateral resistance tests of walls and shaking table tests of masonry building models has indicated, that, qualitatively, characteristic limit states in the seismic behavior can also be well defined by a degree of physical damage observed at each particular limit state, expressed by means of damage indexes.

The analysis of strength and stiffness degradation parameters and energy dissipation capacity of masonry walls and whole buildings also indicated good correlation between the degree of damage and respective parameters under consideration. As can be seen, similar trends in changes in these parameters with the increased degree of damage have been observed for both, masonry walls and whole buildings, for each particular type of masonry construction studied.

Since the observed degree of damage can be correlated with the relevant limit states of seismic behavior of the structure under consideration, damage indexes can be considered as a reliable parameter for the assessment of usability of earthquake-damaged buildings.

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