DISPLACEMENT BASED DESIGN OF MASONRY STRUCTURES UNDER EARTHQUAKE LOADING

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SUMMARY

The present paper introduces a new displacement-based design procedure for masonry buildings under seismic loading. The procedure is based on the capacity spectrum method, in which the reduced response spectrum is superposed with the capacity curve of the regarded structure. The overall capacity curve of the structure is calculated using the individual wall capacity curves stored in a well structured database depending on the masonry type, geometry and loading state. The developed procedure fully utilises the nonlinear bearing reserves of masonry and is generally applicable to all types of masonry.

INTRODUCTION

The current reference method for the seismic design and safety verification of masonry buildings is based on the linear-elastic response spectrum analysis. Two types of this method, a general and a simplified approach, can be distinguished whereas the simplified so-called "lateral force method" can be applied for masonry buildings in most cases since the structural response is not significantly affected by contributions from higher modes of vibration. Basic input of the method is a linear-elastic response spectrum which characterises the seismic site hazard. For considering the ability of energy dissipation the linear-elastic spectrum is reduced by the so-called behaviour factor. The method is a simple approach for the engineering practice in order to avoid time-consuming nonlinear time-history analyses and the concept seems to be justified for material types with high ductility reserves. But for quasi-brittle materials the behaviour factors given in the codes are too conservative and lie for many cases of masonry buildings far beyond the safe side. This issue in combination with the significant increase of seismic loads in the European Standards (Eurocode 8, 2004) leads to problems for the safety verification of masonry buildings all over Europe, even for buildings which have been constructed years ago in seismic active regions and have already proven their stability in practice. Therefore, there is an urgent demand for developing design procedures which are more accurate but still practicable.

In the present paper the development of an innovative design procedure which fully utilises the nonlinear bearing reserves of masonry based on the thesis of Mistler (2006) is presented. The basis of the procedure is the capacity spectrum method, in which the reduced response spectrum is superposed with the capacity curve of the regarded structure. The capacity curve has to be calculated iteratively taking into account the contribution of all relevant shear walls. The wall capacity curves can be determined from cyclic shear wall tests (Ötes & Löring, 2003; Fehling & Stürz, 2006) in combination with simulations using sophisticated numerical

models. Provided that the wall capacity curves are available, the procedure can be used for the design of unreinforced, reinforced, confined and post-strengthened masonry. The effectiveness of the procedure will be demonstrated in the examples of two residential buildings.

DISPLACEMENT BASED DESIGN PROCEDURE

In 1975 Freeman et al. (1975) developed a displacement-based design approach, called capacity spectrum method (CSM). The CSM is a nonlinear static method which compares the seismic action with the load bearing capacity of the building, taking the nonlinear material behaviour with its post-peak capacity into account. The seismic action is represented by a reduced response spectrum due to damping and the building capacity is described by an inelastic cyclic pushover curve. Both curves are converted into acceleration-displacement response spectral ordinates (ADRS format). The intersection point of both curves is called "Performance Point" and corresponds to the maximum spectral displacement for the given site spectrum (see Figure 1). The CSM has been widely used for structural analysis of multi-storey reinforced concrete buildings and the method is included in the guidelines ATC 40 (1996), FEMA 273 (1997) and FEMA 274 (1997). The application of the CSM so far has been rather limited since the approach is based on an equivalent two dimensional cantilever beam without considering torsional effects due to eccentricity of the mass centre.

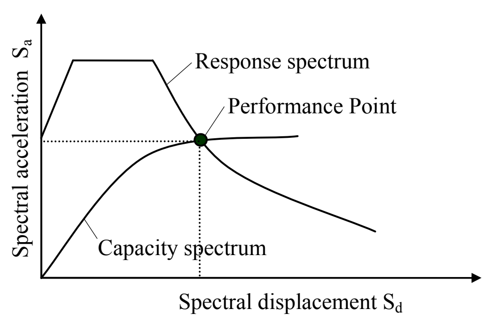

Figure 1. Capacity spectrum method and performance point

CALCULATION OF THE BUILDING CAPACITY CURVE

The procedure assumes continuous shear walls over all stories and floor slabs acting as rigid horizontal diaphragms. Furthermore the out of plane stiffness of the shear walls is neglected. These assumptions, typically fulfilled for most of the existing and planned masonry buildings, lead to a failure mechanism in the ground floor characterised by a large inelastic drift while the upper stories remain linear elastic (Tomaževič et al., 2004). Therefore it is sufficient to represent the capacity of the building by the pushover curve of the ground floor.

The pushover curve of the ground floor is calculated iteratively by imposing a displacement increment Δx (Figure 2) in the direction of the seismic action. Afterwards the resulting forces of all shear walls are calculated using shear wall capacity curves obtained from experimental tests or numerical simulations. In the case of non-symmetric wall configurations the disequilibrium caused by the resulting moment produces a rotation of the system around the mass centre. In order to find the equilibrium for moments M and forces F, the system is rotated by $\Delta\varphi$ and translated by Δy in the perpendicular direction. The resulting pair of

imposed displacement and reaction force in the direction of seismic action is a single point of the pushover curve. The overall pushover curve is calculated by repeating the calculation for different displacements Δ_{GF} (see Figure 2).

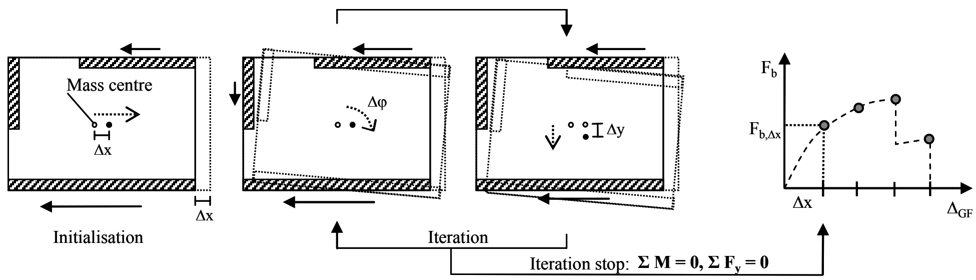

Figure 2. Procedure for the calculation of the pushover curve

TRANSFORMATION OF THE BUIDLING CAPACITY CURVE

According to the basic idea of the capacity spectrum method the pushover curve has to be transformed into the S_a-S_d-diagram. This requires a transformation of each point ($F_{b,i}$, $\Delta_{GF,i}$) into corresponding points ($S_{a,i}$, $S_{d,i}$) using an equivalent single-degree-of-freedom system:

$$S_{a,i} = \frac{F_{b,i}}{M_{Tot,eff} \cdot \alpha_1}, \; S_{d,i} = \frac{\Delta_{GF,i}}{\beta_1 \cdot \phi_{GF,1}} \tag{1}$$

with

$\phi_{GF,1}$ amplitude of the first natural mode at the ground floor,

β_1 modal participation factor for the first natural mode $\underline{\Phi}_1$ of the system,

M_{Tot} total building dead weight plus proportional live loads,

α_1 modal mass coefficient for the first natural mode (ratio of the effective modal mass to the total mass $M_{Tot,eff}$).

The determination of the modal damping factor β_1 and the mass coefficient α_1 requires the calculation of the fundamental natural frequency of the building. Simplified, the building can be idealised as a multi-degree-of-freedom system with horizontal degrees-of-freedom and concentrated masses at the floor slab levels. The fundamental natural frequency must be recalculated for each point of the capacity curve using the updated secant stiffness of the ground floor.

DETERMINATION OF THE PERFORMANCE POINT

The influence of energy dissipation within the nonlinear range of the capacity curve is considered by a reduction of the linear elastic response spectrum by means of an effective viscous damping ξ_{eff}. This damping part considers the material damping as well as the hysteretic damping effects and has to be recalculated for each point of the capacity spectrum. The successive spectrum reduction with the damping value ξ_{eff} transfers the linear response spectrum into a damped spectrum, which fully represent the damping characteristics in dependency on the deformation state. The transformation of the damped response spectrum into the S_a-S_d-diagram can be carried out for each point i of the response spectrum:

$$S_{d,i} = \frac{T_i^2}{4\pi^2} S_{a,i} \tag{2}$$

The calculation of the damped response spectrum allows a direct determination of the "Performance Point", which corresponds to the intersection point of the capacity curve and damped response spectrum in the common S_a-S_d-diagram (see Figure 3). The simple idea of pre-calculating the damped response spectrum avoids the application of time consuming iterative procedures proposed in ATC 40 (1996).

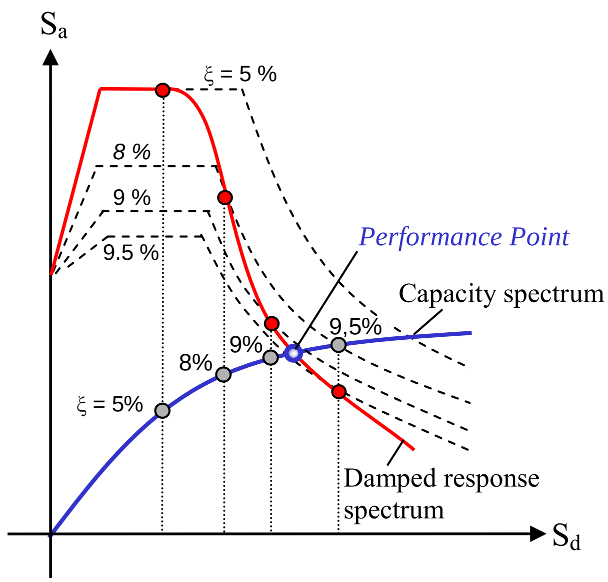

Figure 3. Determination of the "Performance Point" using a damped response spectrum

CALCULATION OF EFFECTIVE VISCOUS DAMPING

The effective viscous damping ξ_{eff} of a building is equal to the sum of the viscous damping ξ_0 and the equivalent viscous damping ξ_{eq}. The viscous damping ξ_0 corresponds to the damping of the building in the linear range and is mainly influenced by the building material and type of connections between the structural components. For masonry the value of ξ_0 ranges between 5 and 7.5 % (Petersen, 1996). The equivalent viscous damping ξ_{eq} represents the hysteretic damping part and can be interpreted as the ratio between the maximum strain energy E_{So} and the hysteretic energy E_D:

$$\xi_{eq} = \frac{1}{4\pi} \frac{E_D}{E_{So}} \tag{3}$$

ATC 40 (1996) proposes a calculation of ξ_{eq} based on a bilinear idealisation of the hysteresis loop. The idealization differs significantly from realistic loops determined from cyclic tests of masonry shear walls. In particular the difference between idealisation and experiment in the highly nonlinear range of deformation is not negligible (FEMA 440, 2005). In order to correct the bilinear idealisation a damping modification factor κ is introduced. Due to the brittle behaviour of masonry ATC 40 (1996) recommends a significant reduction of the hysteresis loop area E_D by modification factor $\kappa = 0.33$.

More realistic is the determination of the equivalent viscous damping ξ_{eq} based on load-displacement curves obtained from cyclic shear wall tests or numerical simulation. Figure 4 shows exemplarily the determination of ξ_{eq} for a wall of optimized perforated clay bricks with a height of 2.50 m, a length of 2.20 m and a vertical load of 1.0 N/mm^2 (Fehling & Stürz, 2006).

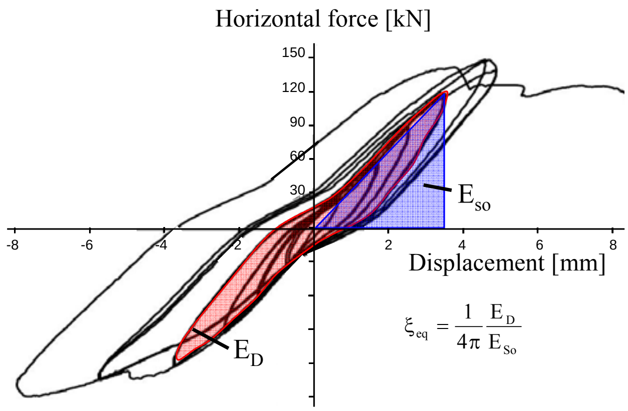

Figure 4. Calculation of the equivalent viscous damping ξ_{eq}

In order to minimise the effort for the determination of the damping values a special tool was implemented into the software package M-DESIGN (2007). This tool provides a graphical user interface for the definition of the hysteresis areas, an automatic evaluation of the damping values assigned to single displacement values and an interpolation scheme to obtain the resulting damping curve for a wall as a function of the displacements. Figure 5 shows a typical effective viscous damping curve for a masonry building depending on the spectral displacement of the first storey.

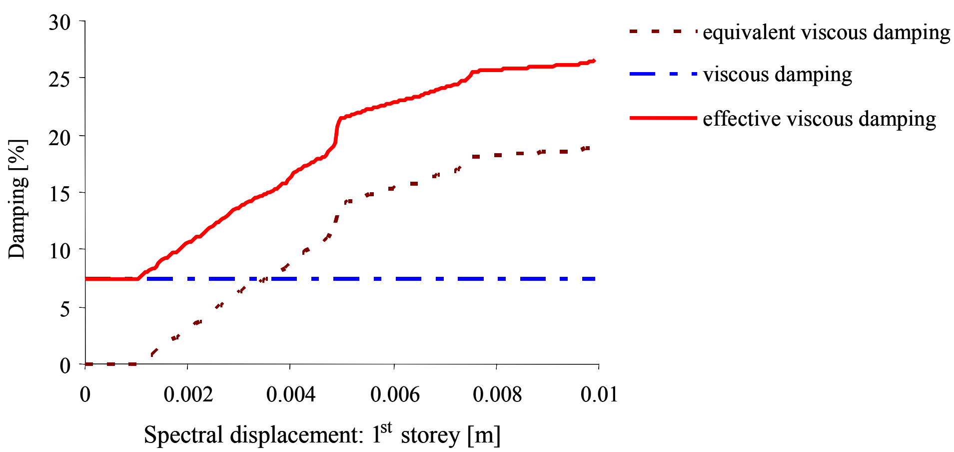

Figure 5. Typical effective viscous damping curve for a masonry wall

By using the damping curves of all shear walls, the overall damping of the building can be calculated for each point of the buildings load-displacement curve by weighting the hysteretic damping of each wall i with the corresponding maximum strain energy $E_{So,i}$:

$$\xi_{eff} = \xi_0 + \frac{\sum \xi_{eq,i} \cdot E_{So,i}}{\sum E_{So,i}} \tag{4}$$

The resulting effective viscous damping ξ_{eff} can be used for the reduction of the linear response spectrum as explained in the previous section. The damping ξ_{eff} must be recalculated for each point of the building's capacity curve depending on the damage grade of each shear wall.

IMPLEMENTATION

The developed displacement-based design procedure was implemented into the software package M-DESIGN (2007). The calculation time is minimised by the storage of all wall capacity curves into a database depending on the masonry type, geometry and loading conditions. Figure 6 shows the architecture of the database with capacity curves obtained by experimental investigations and numerical simulations. Because it is impossible to consider all theoretically possible geometry configurations (height/length: h/l) and loading conditions a feasible interpolation algorithm is linked to the database. By using this algorithm the building capacity curves can be calculated for arbitrary wall configurations as well as geometry and loading conditions of the individual shear walls. Finally, it should be pointed out, that the design procedure is applicable for confined, reinforced and strengthened masonry by means of a simple substitution of wall capacity curves stored in the database.

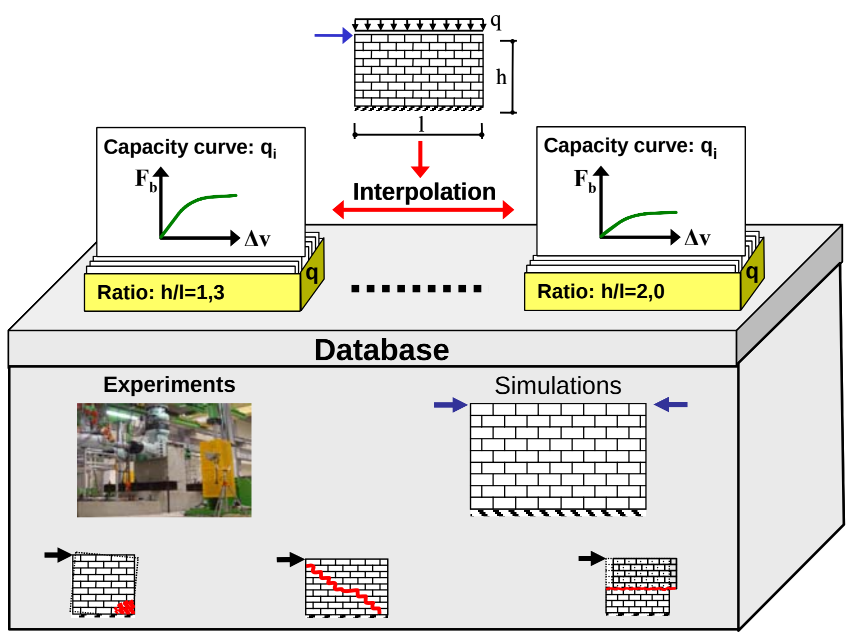

Figure 6. Database architecture for the storage of shear wall capacity curves

APPLICATION EXAMPLE 1: TERRACED HOUSE WITH THREE STORIES

In the following the capacity spectrum method is applied to a typical terraced house with three stories and an inner storey height of 2.50 m. The dimensions of the house are 6.5 m x 13.0 m. The self weight of the reinforced concrete slabs is 5 kN/m². In y-direction two shear walls are spanned over the whole building length and provide sufficient stability against horizontal loads in y-direction and torsional loads. In order to achieve the maximum transparency and flexibility in x-direction only two inner walls with 2.50 m length (W1) and

four outer walls with 1.25 m length (W2) are planned by the architect (Figure 7). The building material are vertically perforated clay bricks (HLZ 12/IIa). The capacity curves of the walls build up of these bricks were taken from experimental investigations (Ötes & Löring, 2003).

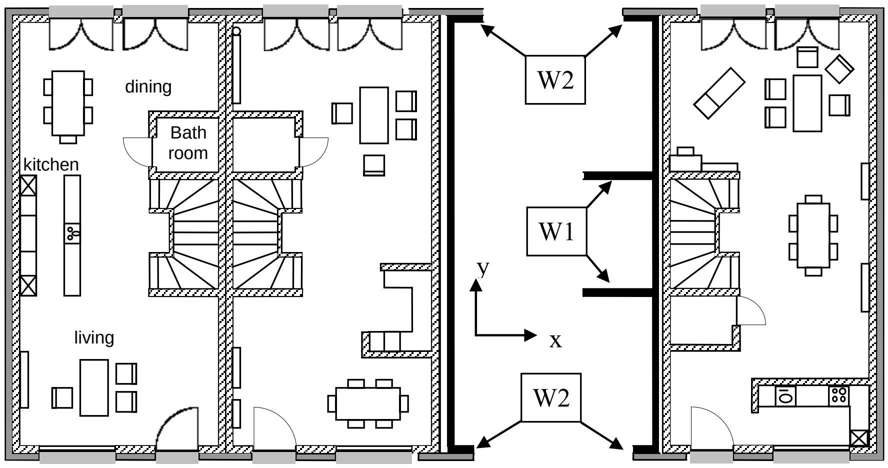

Figure 7. Ground plan of the terraced house

Figure 8 shows the pushover curves of the walls W1 and W2 obtained by averaging the envelopes in positive and negative deformation direction. The overall pushover curve of the ground floor in x-direction corresponds to a simple superposition of the wall capacity curves. An iterative calculation is not necessary because of the symmetry of the ground plan and wall configuration.

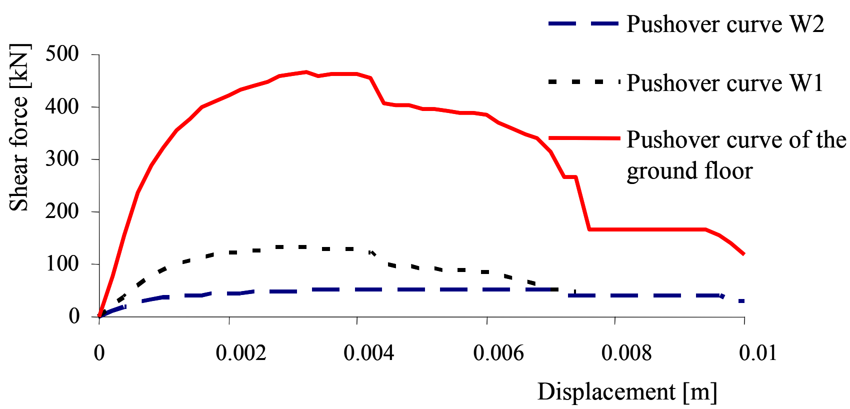

Figure 8. Wall pushover curves and overall pushover curve of the ground floor

The seismic action is described by a linear response spectrum according to DIN 4149 (2005) for seismic zone 3 and subsoil condition B-R. By transforming the response spectrum and the pushover curve into the S_a-S_d-diagram the “Performance Point” as intersection point of both curves was calculated iteratively (Figure 9). The “Performance Point” lies in the nonlinear range of the capacity spectrum. Nevertheless the structural stability is ensured for the given seismic action.

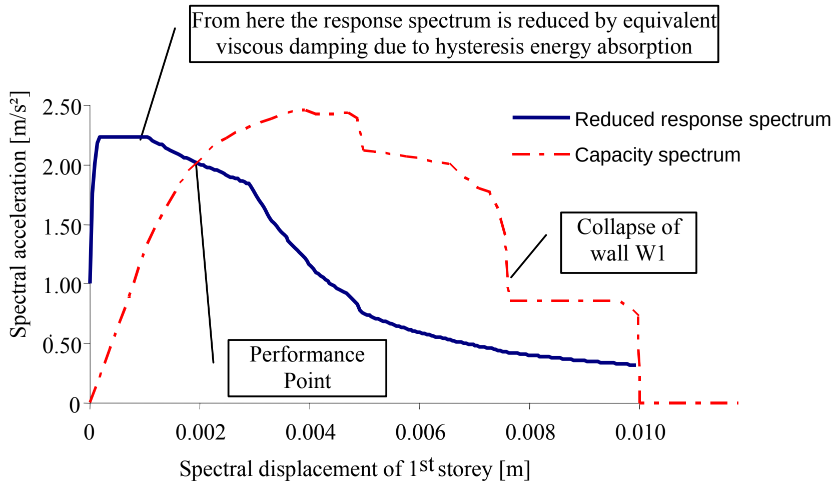

Figure 9. Determination of the “Performance Point”

APPLICATION EXAMPLE 2: FOUR STOREY BUILDING

The second example demonstrates the application of the design procedure on the example of a four storey house with an eccentricity between the mass centre M and the stiffness center S due to an irregular ground plan (see Figure 10). The dimensions of the house are 6.0 m x 9.0 m and the inner storey height is 2.50 m. The self weight of the reinforced concrete slabs is 6.5 kN/m². Furthermore a live load of 1.5 kN/m² was applied on each floor level. The seismic action in lateral building direction is represented by a linear response spectrum according to DIN 4149 (2005) for seismic zone 3 and subsoil condition A-R. The capacity curves of the walls were taken from experimental investigations (Fehling & Stürz, 2006).

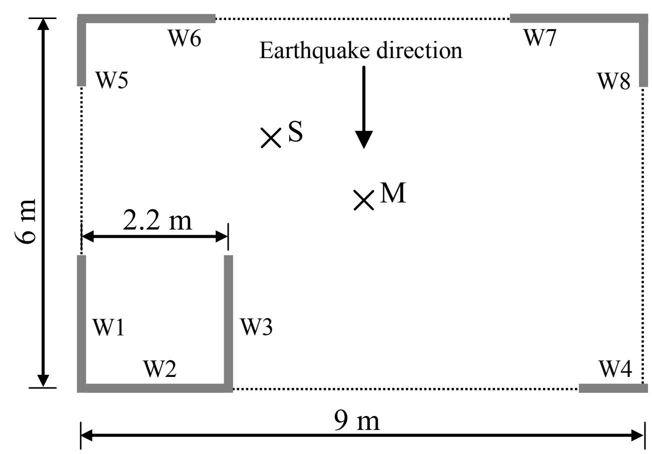

Figure 10. Irregular ground plan of the four storey building

The “Performance Point” of the damped response spectrum and the capacity curve lies in the rising branch of the buildings capacity curve (Figure 11). For this reason the building exhibits nonlinear bearing reserves and the structural stability for the applied seismic load level is ensured. The damage of the horizontal load bearing system starts with failure of wall W8,

followed by failure of W3 and W1. Finally the load bearing system in the lateral direction collapsed with failure of wall W8. The successive failure of the walls leads to a stepped capacity curve (Figure 11) in which each step corresponds to a failure of a single wall.

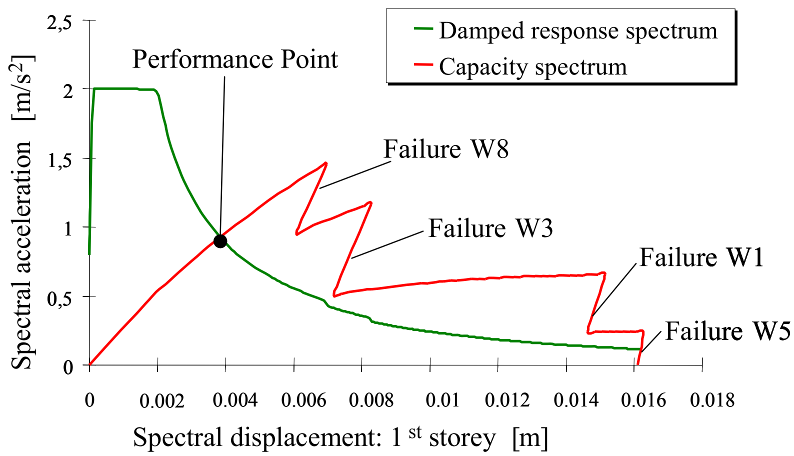

Figure 11. Performance point of the four storey building

CONCLUSIONS

The present paper introduces a new displacement based design approach for masonry structures based on the capacity spectrum method. The building capacity curve is calculated iteratively using capacity curves of single shear walls. The wall capacity curves are stored in a well structured database depending on the masonry type, geometry and loading conditions. The design procedure fully utilises the nonlinear bearing reserves and is applicable for all types of masonry. Further research is needed to estimate the level of constraint at each floor level due to the bending stiffness of the floor slabs. The boundary conditions at the top of the wall strongly influence the results of the shear wall tests and numerical simulations. But it has to be kept in mind, that a general estimation is quite complex because the level of restraint is affected by the wall configuration, the stiffness of the slabs, the geometry of the walls and the vertical load level. Furthermore the procedure should be extended to arbitrary wall configurations in each storey and wall failures in all stories. However, the procedure seems to be a promising way to verify the safety of masonry structures under lateral loading due to earthquake and wind loads.

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