presented at the 6th Weimar Optimization and Stochastic Days 2009
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Probabilistic Seismic Risk Assessment of Masonry

Silvio T. Sperbeck[1,2*], Harald Budelmann[1]

[1] Institute of Building Materials, Concrete Construction and Fire Protection, Technische Universität Braunschweig, Braunschweig Germany

[2] International Graduate College 802, Technische Universität Braunschweig, Braunschweig, Germany

Summary

A huge amount of historical as well as modern structures is made of masonry which is usually notorious to have a low earthquake resistance limited by low shear strength and lowl ductility. In order to improve shear capacity and ductility, vertical local prestressing is considered. Static cyclic tests have shown the suitability of this method. A detailed investigation of the dynamic behaviour is demandable before using the strengthening method against earthquake action. The large quantity of necessary experimental tests is very expensive. This contribution presents possibilities, based on probabilistic numerical methods, to investigate the usefulness of vertical prestressing with particular emphasis on the dynamic behaviour as well as to estimate the risk. The work uses a risk based design, which accounts also for several damage stages, in order to assess the benefit of prestressing more in detail. For the transient earthquake simulations a macro modelling method by means of the material model of Lagomarsino and Gambarotta is used in combination with the finite element program ANSYS®. This allows a prediction of damage via special damage parameters for units and mortar separately. Several detected factors that influence masonry behaviour and numerical results are investigated and discussed. The probabilities of damages are estimated by means of probabilistic methods. Thereto, Latin Hypercube sampling is applied by means of the advanced program optiSLang® in combination with ANSYS®, in order to carry out dynamic probabilistic analyses. With the calculated damage probabilities, the risks are estimated and the benefits of vertical prestressing in case of seismic action are compared.

Keywords: Masonry, Prestressing, Earthquake, Risk Management, Probabilistic

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[*] Kontakt: Dr.-Ing. Silvio T. Sperbeck, iBMB, Beethovenstr. 52, D-38106 Braunschweig, E-Mail: s.sperbeck [@] ibmb.tu-bs.de

1 Introduction

The enormous number of damages on masonry structures located in seismic areas shows the necessity to investigate and to improve the load carrying behaviour of masonry. Bracing walls of houses are mainly loaded in horizontal direction during an earthquake. Thus, the in-plane shear behaviour of masonry walls is of highest interest in this work. Detailed descriptions of masonry shear behaviour are given for instance in Van der Pluijm (1993) and Lourenço (1996). Unreinforced masonry has a low resistance against seismic action. On the one hand, this is caused by the limited shear capacity, especially for structures with low vertical loading, and by its low ductility on the other hand. Also in masonry walls, the simple friction law is valid. While increasing the vertical loading, the horizontal resistance is improved as well. Since, higher masses lead to higher inertia force, vertical prestressing / post-tensioning are interesting rehabilitation measures. This contribution refers to vertical local prestressing of masonry walls by means of tendons or strands. Tendons are placed in the walls to reduce cracks in the bed joints and to increase the shear capacity.

An increase of the elastic range is often not sufficient to design structures with a high seismic performance especially in case of strong earthquakes. Modern concepts take into account also the plastic behaviour for economic designed buildings. A comparison is illustrated in Fig. 1.

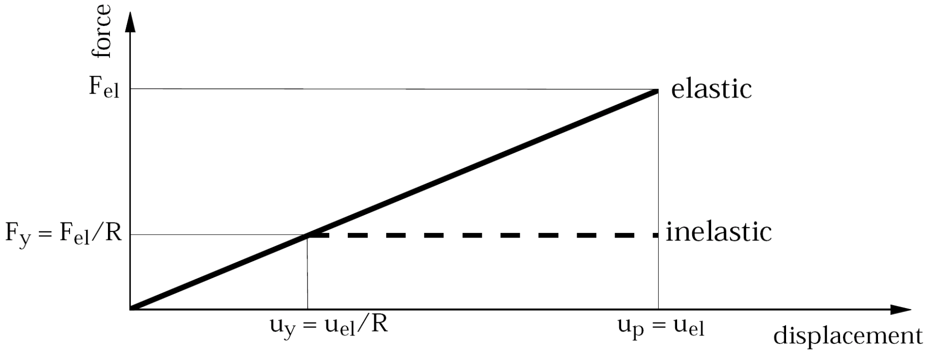


Fig. 1: Comparison of elastic and inelastic response.

Plastic behaviour reduces the earthquake loading and avoid brittle failure due to an insured high ductility. However, plastic deformations are a kind of damage on the structure. Whereas, an increased elastic range does not reduce the seismic loading. In case of brittle behaviour at the end of the big elastic part, would lead to brittle collapse. Since, the real earthquakes do not know the strength of the design earthquakes, the first may be stronger and dangerous collapse would occur. These phenomena have to be considered also in case of prestressing. Detailed explanations are given in the following. In order to assess the benefit of prestressing more in detail, a risk based design is used that accounts also for several damage stages. Deeper descriptions are given below. The probabilities of damages are estimated by means of probabilistic methods using LHS with the optiSLang®.

2 Management of disaster risk

The purpose of this contribution is to get a more detailed insight into the impact of load and material uncertainties with respect to masonry subjected to seismic action. It is important to realize, that this work is done in the context of giving a prediction of the probability distribution of possible damage states, not to assess the structural safety itself. Therefore, an unified risk management concept is applied (see Fig. 2).

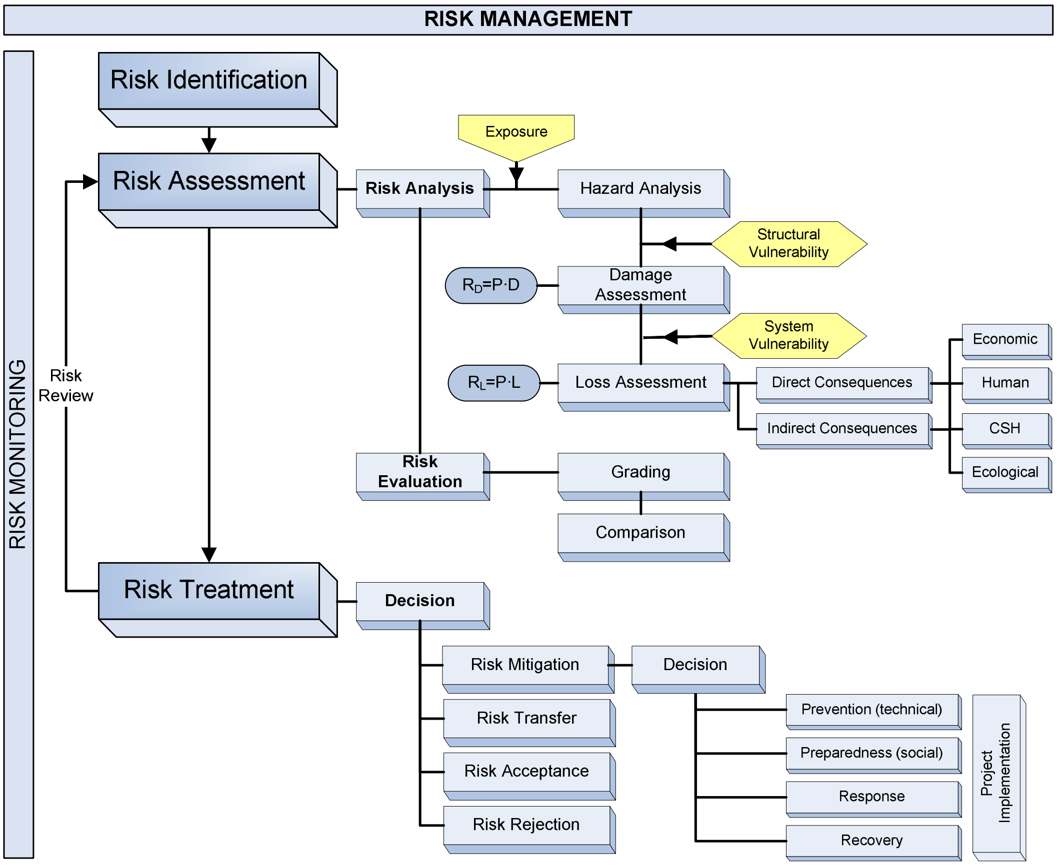


Fig. 2: Overview of the whole risk management process (Pliefke et al. 2007).

The concept results from a long development process for the International Graduate College 802. The interested reader is referred to Pliefke, Sperbeck, Urban (2006) and (Pliefke et al. 2007). The approach covers the whole risk management chain, starting from risk identification over risk assessment up to risk treatment. The methodology is too exhaustive to be applied completely in the framework of this work. The main parts to reach the aim are the hazard analysis of the seismic peril, the damage analysis to estimate the structural damage D and the risk mitigation by means of the technical prevention with prestressed strands. The calculated so-called structural risks R_D are evaluated by a comparison. The total risk R_L – taking also into account further consequences as economic losses L – is not part of this contribution. The risk calculation schemes are integrated in the concept (see Fig. 2). Different definitions as well as ways to estimate and evaluate risk may be found in literature. Here, the definition risk R is equal to damage D times its probability P is applied.

3 Experimental Investigation

Experimental tests with internal prestressed masonry walls of Budelmann et al. (2004) have indicated such a ductile behaviour. Four different wall systems have been investigated in static cyclic tests and are used to calibrate the numerical models which are mainly focused on wall 1 and wall 3. The experimental set-up is depicted in Fig. 3. The width of the wall, the distance between the tendons and the boundary conditions are varied.

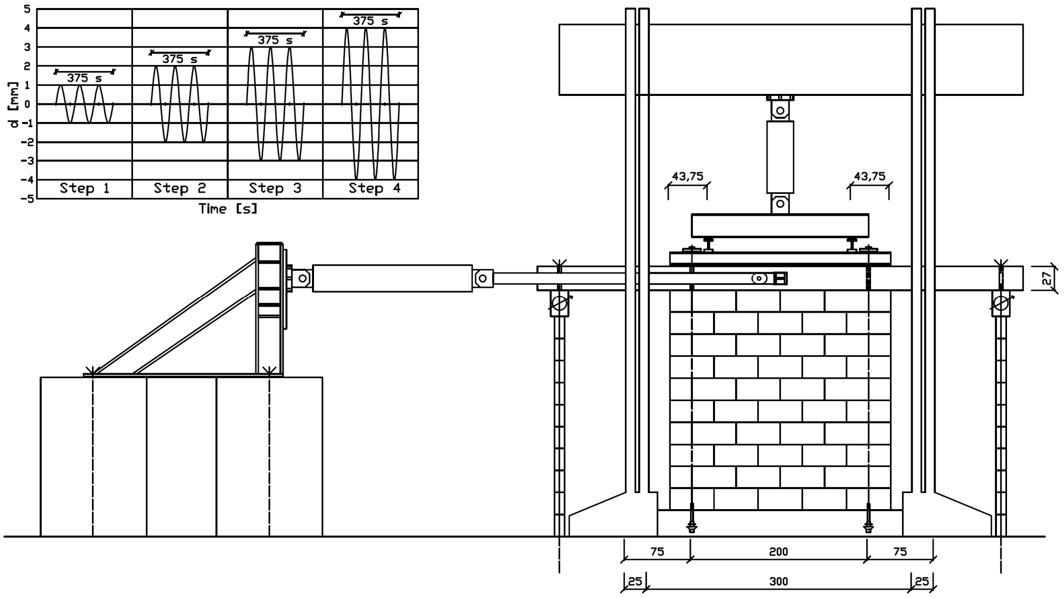


Fig. 3: Experimental set-up of wall 1 (Budelmann et al. 2004).

Usually, higher vertical loading causes more brittle failure. However, the investigated walls behaved ductile, despite the additional vertical loads. It is particularly shown in which cases vertical prestressing leads to an increased ductility or not in Sperbeck (2008). Internal tendons with bond lead to higher ductility than external tendons, since internal ones tie up the masonry in-between the tendons and prevent so a brittle collapse which would occur by sliding down of the upper wall triangle.

4 Deterministic Simulations

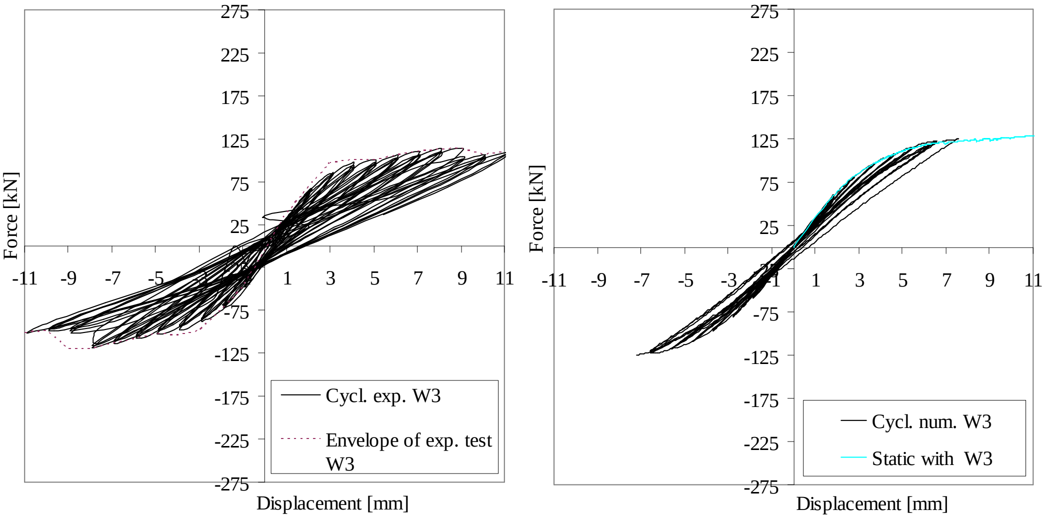
A comparison of different possible simulation techniques and material models is given in Sperbeck (2008). Regarding the aimed probabilistic dynamic simulations the material model of Gambarotta & Lagomarsino (1997) is applied. Since, such simulations are very time consuming this efficient constitutive model is chosen. However, it is adequate accurate based on fracture mechanics and macro modelling. The model is previously checked in deterministic simulations regarding different experimental tests and parameter studies. Regarding the output of all simulations, the damage parameters of Tab. 1 are of interest. Very important are here the global and local unit damage as well as the global and local mortar damage. A detailed descriptions may be found in Sperbeck (2008).

Tab. 1: Notation of the used damage parameters

Symbol	Abbreviation	Damage parameter
max $\lvert u_{h,rel} \rvert$	uhrel	Absolute maximal horizontal top displacement
max $\alpha_{b,loc}$	SRATloc	Maximal local unit damage
max $\alpha_{b,glo}$	SRATglob_av	Maximal average global unit damage
max $\alpha_{m,loc}$	EPEQloc	Maximal local mortar damage
max $\alpha_{m,glo}$	EPEQglob_av	Maximal average global mortar damage
max ε_{pleq}	EQV	Maximal plastic equivalent strain
max ε^{pl}_{xy}	EPPLXY	Maximal plastic shear strain
max $\varepsilon^{pl}_{y,t}$	EPPLYtens	Maximal vertical plastic tensile strain
max $\varepsilon^{pl}_{y,c}$	EPPLYcomp	Maximal vertical plastic compression strain

4.1 Static cyclic simulations

First of all, the experimental static cyclic tests of prestressed walls - described above - are utilized to calibrate the numerical models. For wall 3, a comparison of experimental and numerical results is exemplarily shown in Fig. 4. The results fit well, also degradation of stiffness could be modelled realistically. In Fig. 4b, the static calculation is given. The difference between static and static cyclic loading in not significant in this case. So, the degradation of strength is less important. In addition, the walls are modelled without prestressing. The numerical results fit well to the expected behaviour.



(a) Experimental results with envelope (b) Numerical results with static curve

Fig. 4: Horizontal load displacement diagrams of wall 3 – static cyclic curve

4.2 Dynamic Simulations

Experimental dynamic tests are very expensive and could not be funded in the framework of this project. Such investigations cannot be financed especially, if scattering shall be taken into account. It would lead to an enormous number of shaking table tests. Therefore, it is investigated numerically on the base of the previous elucidated masonry walls. It is assumed, the walls would be bracing elements of a three storey tarraced house in the region of Aachen, Germany. The applied earthquakes are artificially generated for different return periods. In the next chapter, the hazard analysis and their scatter are explained that are applied for the small wall 3. For the deterministic dynamic analyses, the mean values of the earthquake loading are used. Wall 1 has a higher resistance as the small wall 3. Therefore, stronger earthquakes are applied.

The deterministic results are different regarding the impact of prestressing for some damage parameters depending on the applied earthquake. For instance, the local unit damage can be reduced or increased due to prestressing. In Fig. 5, the unit damage of wall 1 is compared for the prestressed and the non-prestressed version. If prestressing is useful depends also on the exact point of time during the earthquake. Probabilistic analyses are carried out to observe trends regarding this inconsistent impact also.

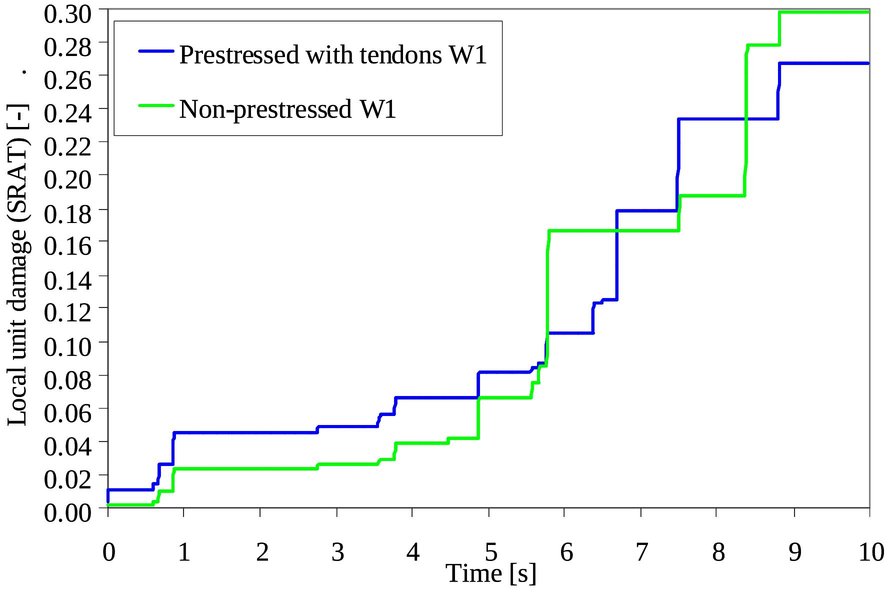


Fig. 5: Process of local unit damage, wall 1, high earthquake loading

5 Probabilistic Simulations and Risk Assessment

5.1 Hazard Analysis

The region of Aachen in Germany is assumed as the site for this fictive example. As a base, the results of a probabilistic seismic hazard analysis PSHA carried out by Schmitt (2005) are used. The analysis methodology is resting upon the conception that the seismic hazard at a site is a function of three main components: the space geometry of seismic sources, the characteristics and statistics of their seismicity and the attenuation of intensity. This hazard curve displays the annual probability of the intensity regarding the Medvedev-Spoonheuer-Karnik (MSK) scale which is displayed in Fig. 6 for this region.

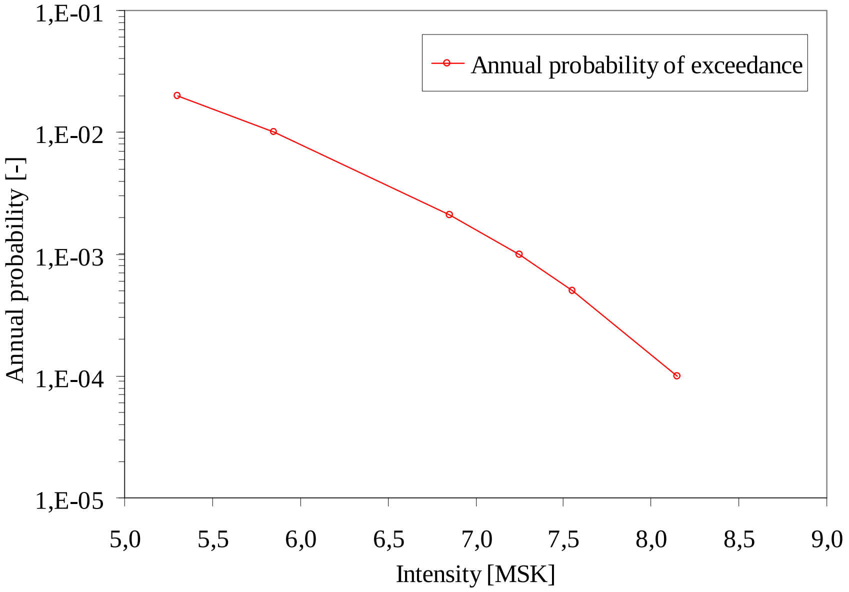


Fig. 6: Seismic hazard curve for Aachen, Germany (Schmitt 2005)

An investigation of the whole range of probabilities (see Fig. 6) is not reasonable by means of probabilistic transient analyses, since many small earthquakes which occur with high probability do not lead to damages. A huge number of transient calculations is dispensable, while not leading to damage. Thus, the following new method is suggested and applied in this study. A minimum threshold is selected which is reasonably fitted to the investigated structure. Therefore, the minimum threshold corresponds to a return periods of 475 years in this work, and the maximum to a return period of 10000 years. Moreover, a return period of 2000 years is used for the subsequent risk based analysis. For the transient simulations, time histories are necessary. The PGAs given in Tab. 2 are used to generate an aim response spectra for each return period of interest.

Tab. 2: Seismic hazard data for the region of Aachen, Germany (Schmitt 2005)

Return period [a]	Annual probability of exceedance [-]	Annual probability of exceedance [%]	Intensity [MSK]	PGA [m/s²]
50	0.0200	2.00	5.30	0.38
100	0.0100	1.00	5.85	0.52
475	0.0021	0.21	6.85	0.92
1000	0.0010	0.10	7.25	1.15
2000	0.0005	0.05	7.55	1.37
10000	0.0001	0.01	8.15	1.94

Corresponding to each aim response spectra of every investigated return period, four time histories are artificially generated that differ in duration and characteristics. For the return period of 475 years the data is given in a pseudo-velocity diagrams (Fig. 7). In the probabilistic transient structural analyses, the acceleration scatter additionally by means of a scaling factor, within a range of a lognormal distribution with a standard deviation of 0.6 and a mean value of 1.0 in accordance to Rackwitz (2006) and several other authors.

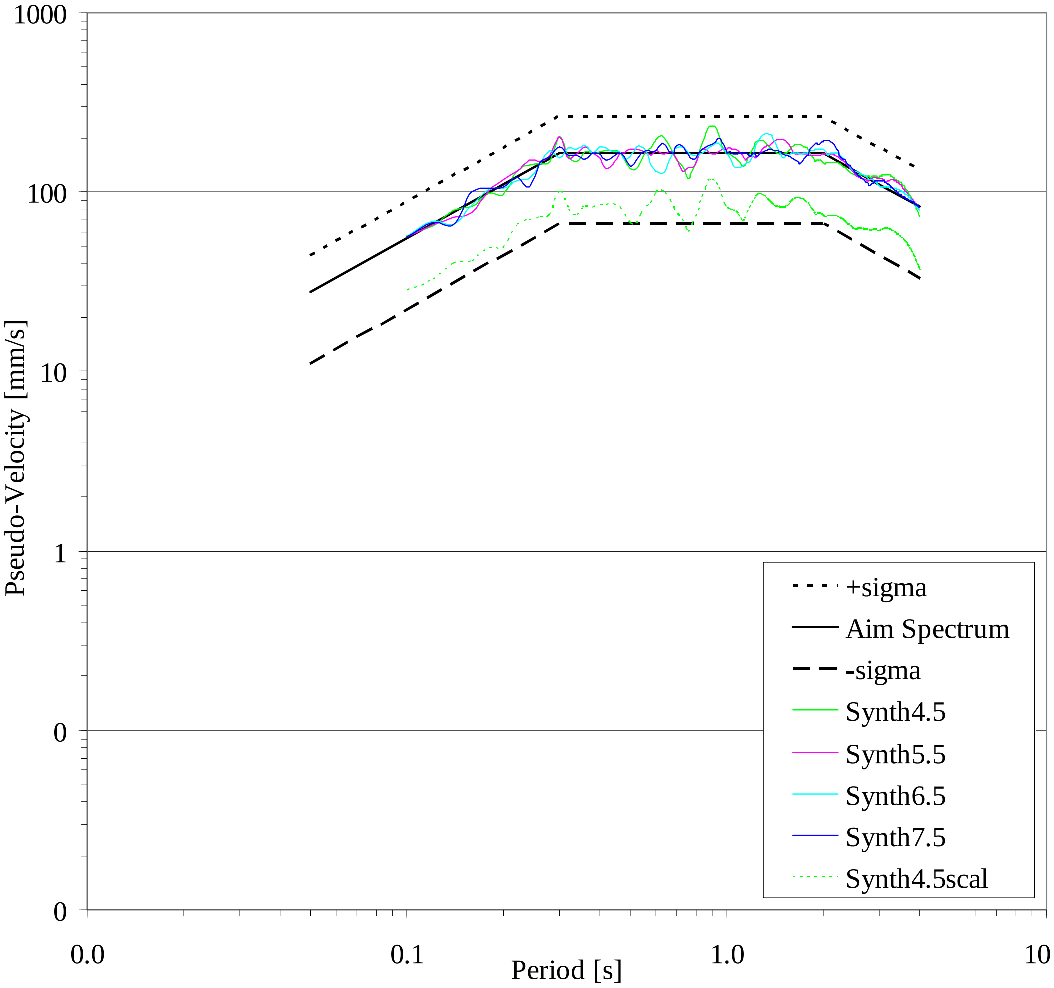


Fig. 7: Pseudo-velocity diagram for the return period of 2000 years

5.2 Damage Analysis

For the probabilistic dynamic simulations, Latin Hypercube sampling with the advanced program optiSLang® and the calibrated material input parameters are used, here as mean values. The uncertainties of material resistance are considered by means of probability density functions PDFs, as given in Tab. 3. Here, a change of the support condition is taken into account, regarding the stiffness of the floor slab. The assumed scatter of loading is presented in Tab. 4.

Tab. 3: Varied parameters and applied distributions for wall 3 return period 475 a

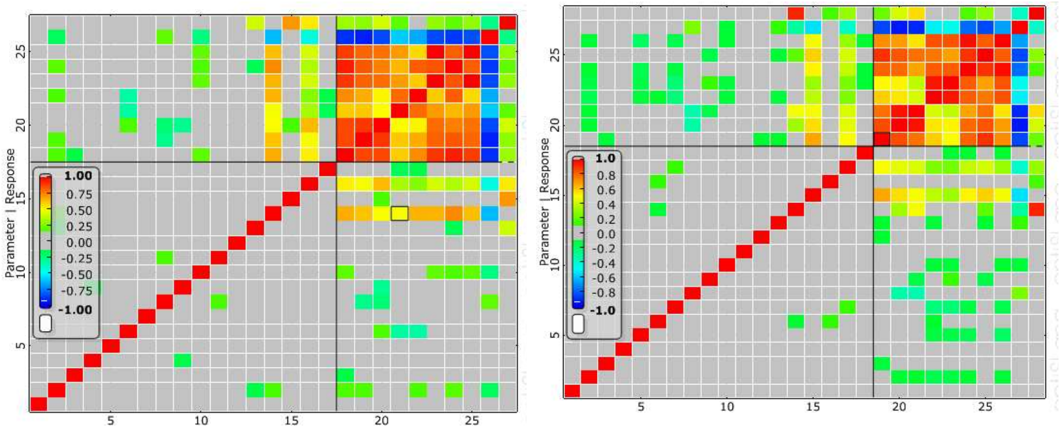
Symbol	Abbr. in files	Variable	Distribution	Expected/ mean	Standard deviation	Min.	Max.
Masonry:							
η	nuxy	Poisson ratio	lognormal	0.15	0.0375	-	-
ρ_M	dens	Density of masonry	normal	1.65e-9 to/mm^3	0.12375e-9 580	-	-
E_M	emod	Young's Modulus of masonry	normal	5800 N/mm^2	0.0807	-	-
μ	fric	Friction coefficient	lognormal	0.436	0.3045	-	-
σ_{mr}	mtens	Tensile strength of mortar joints	lognormal	0.87 N/mm^2	0.132	-	-
τ_{mr}	mshea	Shear strength of mortar joints	lognormal	0.44 N/mm^2	-	-	-
c_{mt}	IDPGm	Inelastic deformation parameter for mortar	uniform	0.95	2.924	0.5	1.5
σ_{br}	comp	Compressive strength of masonry	lognormal	17.2 N/mm^2	0.375	-	-
τ_{br}	bshea	Shear strength of masonry	lognormal	2.5 N/mm^2	-	-	-
c_{bt}	IDPEb	Inelastic deformation parameter for masonry	uniform	1.1		0.6	1.55
Support condition - Stiffness of the concrete floor slab:							
E_C	Emod-Con	Young's Modulus of concrete	truncated normal	14000 N/mm^2	5600	0.1	47600
Damping:							
α	adamp	mass damping	uniform	0.62	-	0.4048	0.8352
β	bdamp	stiffness damping	uniform	0.0003	-	0.0001	0.0005

Wall 1 and 3 are modelled in a non-prestressed and a prestressed version in order to analyse the impact of prestressing on damage and its probability. Wall 1 is subjected to strong earthquakes of only one high return period to avoid a response only in the elastic range, which is not reasonable for the damage assessment. An extensive probabilistic damage assessment is carried out for wall 3 in order to estimate risk. In case of this wall, six different probabilistic simulations are carried out for three different seismic load levels regarding the return periods of 475, 2000 and 10000 years as explained above. The damage assessment of wall 3 based on the generated accelerograms of the hazard analysis takes into account the uncertainties of seismic loading in a manner already described.

Tab. 4: Varied load parameters and applied distributions for wall 3

Symbol	Abbr. in files	Variable	Distribution	Expected/ mean	Standard deviation	Min.	Max.
Loading:							
P	PreFo	Sum of prestessing	lognormal	352000 N	123200	-	-
ρ_M	head-mass	Density of upper structure parts	truncated normal	2.29358e-7 to/mm^3	0.91743e-7	1e-10	1.15e-6
D	durat	Earthquake s.s. duration	discrete uniform	-	4.5, 5.5, 6.5, 7.5	4.5	7.5

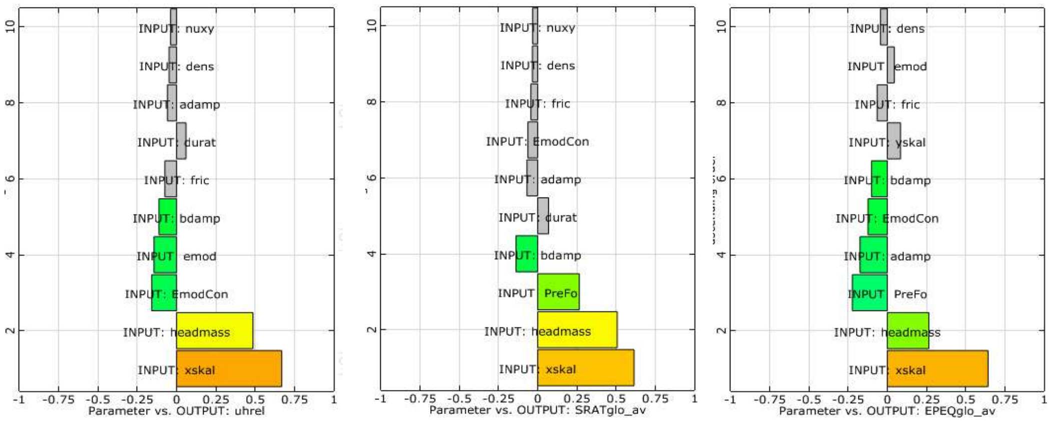
The results of the probabilistic analyses are sensitivities of input and output parameters, as well as PDFs for the predicted damages. A correlation matrix gives an overview of sensitivities via collared illustration of the correlation coefficients. The left matrix misses one line and one row for the variable prestress level. The correlation matrices are very similar for the non-prestressed and for the prestressed wall (see Fig. 8).



(a) Non-prestressed (17 input parameters) (b) Prestressed (18 input parameters)

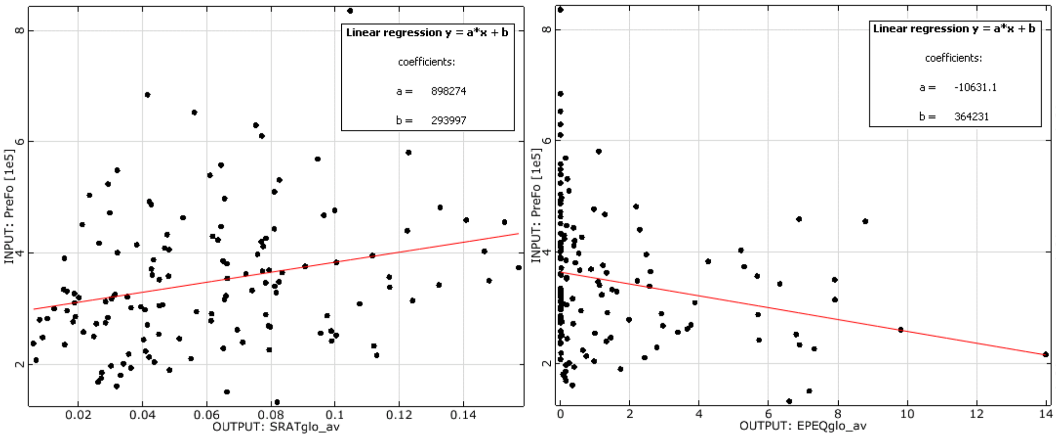
Fig. 8: Correlation matrices of wall 3 for a return period of 475 years

All output parameters are highly correlated with each other. Not so the mortar damages with the storey drift and the unit damage. This becomes smaller in case of prestressing. The bar charts with linear correlation coefficients as partly given in Fig. 9 show negative correlations of many material parameters with the damage. This means for instance: the higher the strength, the lower the damage. All damage parameters are mainly influenced by the horizontal excitation (xskal) and the mass of the upper storeys (headmass). The prestressing level (P) correlates very well with the global unit damage and is negatively correlated with the global mortar damage. Consequently, the higher the prestressing, the higher the unit damage, the lower the mortar damage. The damping (adamp and bdamp) has also a small impact on some damage parameters as well as the stiffness of the concrete floor slab (EmodCon). These trends can be observed also for wall 1 and for the other return periods. Moreover, the stronger the earthquakes, the better the correlations and more significant the impact of xskal and headmass. All these results are very plausible and go in line with deterministic results of previous investigations, experimental tests and the literature. Regarding the mortar and unit damage, a clear trend can be observed in the results of the probabilistic simulations. Fig. 10 shows an increase of unit damage due to prestressing, while the mortar damage is reduced in case of seismic action.



(a) Storey drift (b) Global unit damage (c) Global mortar damage

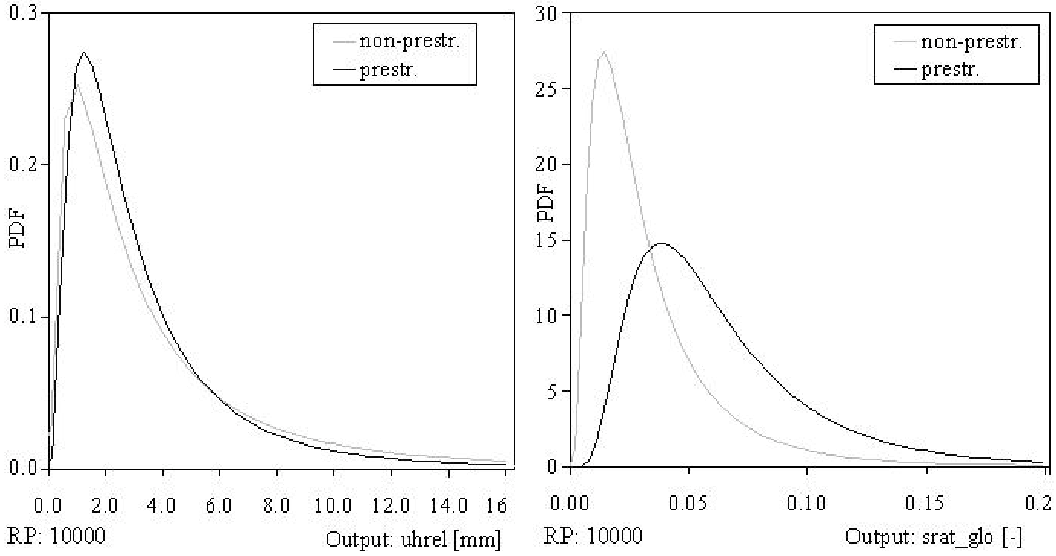
Fig. 9: Linear correlation coefficients, prestressed wall 3, a return period of 10000 years



(a) Global unit damage (b) Global mortar damage

Fig. 10: Linear correlation coefficients of the non-prestressed wall

Resulting PDFs for the storey drift and the global unit damage are exemplarily depicted in Fig. 11. The deterministic results show a small impact of prestressing on the drift that is confirmed by the PDFs, since there are only small differences. Not so the unit damage, neither for the deterministic simulation, nor for the probabilistic ones a small impact exists. The probability of great unit damages increases due to prestressing, while the probability for small damages decreases significantly. For mortar damage, it is the opposite.



(a) Horizontal relative displacement (b) Global unit damage

Fig. 11: Probability density functions for a return period of 10000 years for wall 3

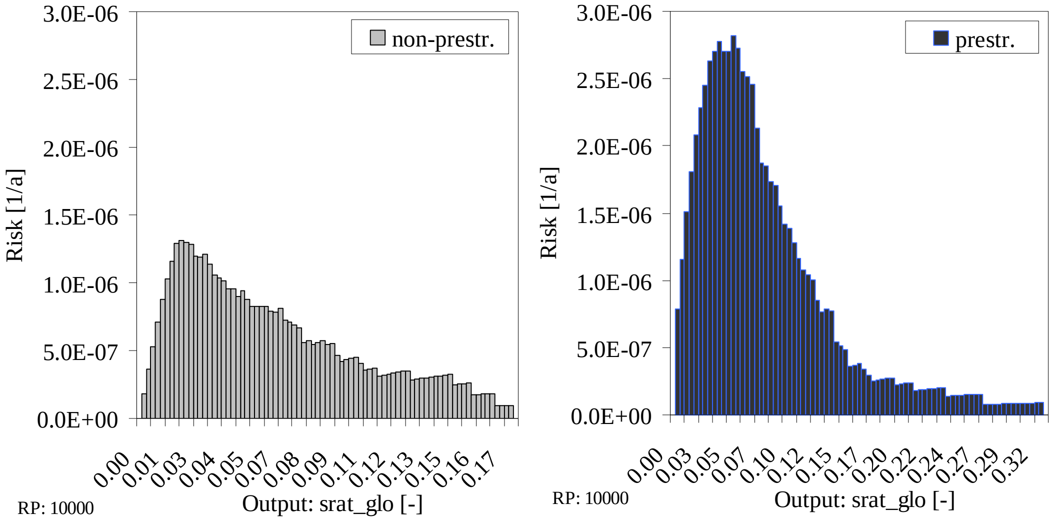
5.3 Risk Calculation and Risk Comparison

To calculate and compare risks, the focus lies on the structural risk R_D in this work (see Fig. 2). As a result of the hazard analysis, the hazard curve given in Fig. 6 and discrete values in Tab. 2, provides the needed probability of exceedance of the hazard $p_{ex}(H)$ for each of the investigated return periods. The structural risk R_D is calculated by means of $p_{ex}(H)$ and the 'damage probability' $p_{ex}(L,R)$ due to resistance and load scatter as a result of the probabilistic damage analysis (see equation (1)).

$$R_D = p_{ex}(H) \cdot p_{ex}(L,R) \cdot D \tag{1}$$

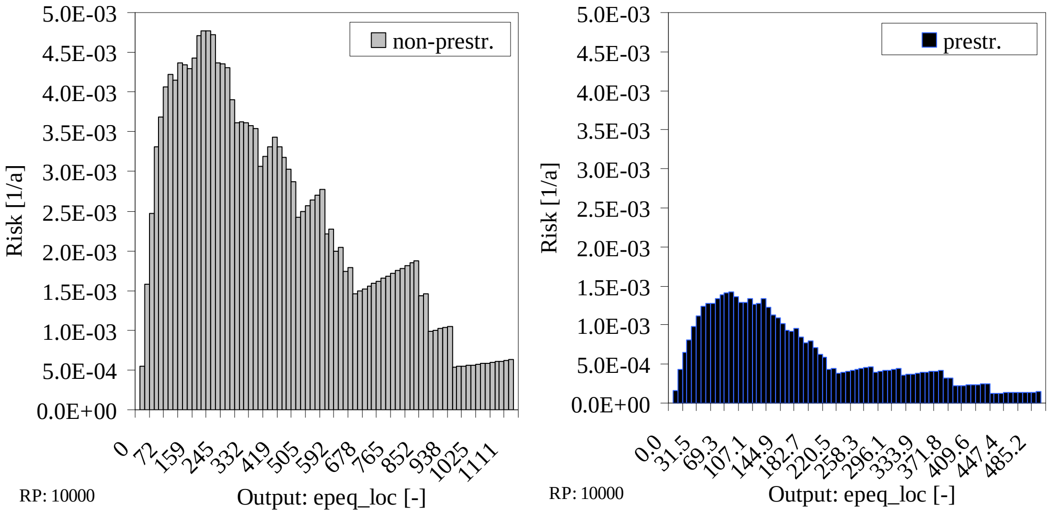
$p_{ex}(H)$	Probability of exceedance of the hazard
$p_{ex}(L,R)$	Probability of the damage due to resistance and load scatter
D	Damage degree

On the one hand, load means the level of prestressing and dead load, here in terms of 'head mass'. On the other hand, the load intensity of an earthquake, which can scatter as well for each return period. The last is considered by means of the scaling factors Xskal and Yskal for the horizontal and vertical acceleration histogram and different durations D. Instead of the fitted PDF, the sampled histograms of the probabilistic damage analyses are directly used to avoid inaccuracy and errors. The calculated risks of global unit damage are exemplary presented in Fig. 12. Moreover, the risks for local mortar damage are given in Fig. 13. Also the risk distributions show an increase of the unit damage due to prestressing and a decrease in case of the mortar damage. The trends are confirmed by static and dynamic simulations. In general, the equivalent plastic strain, plastic shear strain and vertical plastic tensile strain are reduced by prestressing as well.



(a) Non-prestressed wall 3 (b) Prestressed wall 3

Fig. 12: Risk distribution of the global unit damage for a return period of 10000 years



(a) Non-prestressed wall 3 (b) Prestressed wall 3

Fig. 13: Risk distribution of the local mortar damage for a return period of 10000 years

6 Conclusion

To judge on the usefulness of vertical prestressing the probabilistic damage based design of risk management was very helpful. The advanced extensive numerical investigation with optiSLang® got a deeper insight and exhibited several problems. The question whether the application of prestressing on earthquake loaded masonry is useful cannot be answered generally. It is to distinguish between several cases depending on the structure, degree of seismic excitation, existence and level of other vertical loading as well as means of practical execution. Since, high vertical loading and missing wall-tendon interaction lead to brittle collapse, prestressing can be dangerous. Thus, external prestressing especially with high prestressing degrees may cause brittle failure, if high earthquake intensities exceed the shear capacity. Therefore, high prestressing forces cannot be recommended. For regions of high seismicity, a well ductile behaviour has to be ensure by means of further measures, if external prestressing is applied. In regions of low seismicity, the ductility is less important, if a sufficient safety factor guarantees lower horizontal loading than shear resistance. The increased elastic range leads to lower damages up to activation of plasticity. As an advantage, the mortar damage is always decreased by prestressing. However, it is not as important as the unit damage that is in general increased. The same trends are valid for the related risks. For a detailed description the interested reader is referred to Sperbeck (2008).

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