

## COMPUTATIONAL DAMAGE MEASURE FOR RC FRAME STRUCTURES UNDER SEISMIC LOADING

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**Abstract.** *In the earthquake areas, the priority task in seismic design is to fulfill the safety requirements with respect to the expected earthquakes. These safety requirements will differ from each other according to the type of the earthquake and structure. For that reason, most codes for seismic design, assessment and retrofitting use the performance-based seismic design concept. In that concept, performance levels are specified ranging from fully operational to near collapse and earthquake design forces are classified. Such performance levels are then associated with a damage state with respect to a given earthquake. At that, either descriptive criteria or displacements are utilized for the damage extent instead of an explicit damage index. The aim of this work is to overview existing damage indices and to define new explicit damage indices which may be used as seismic design criteria for reinforced concrete frames.*

*Both local and global damage indices to be defined will range between 0 (no damage) and 1 (failure or collapse). They will be suitable for static, cyclic and dynamic computer analysis in order to be used with various existing design procedures.*

*The necessary computer analyses are carried out by means of the finite element program (FRAME) developed in-house within the MATLAB environment. In that program, classical rectangular beam elements are used. Elasto-plastic bilinear moment-curvature relationships are used for the nonlinear material model including hysteretic behaviour under cyclic and dynamic loading. The stiffness matrices of the elements are obtained by use of the spread plasticity model along the length. The Newmark-Beta method with constant average acceleration is applied for the step-by-step time integration of the governing equations.*

*The cyclic global damage index is proposed to be composed of the separate global damage indices during positive and negative load cycles. Several test problems have been analysed to check the sensitivity of the computational global damage measure for cyclic and dynamic loadings.*

## 1 INTRODUCTION

In the seismically active areas, it is necessary to estimate the damage level of the existing and new structures that have experienced or will experience one or more earthquakes. Most codes for seismic design, assessment and retrofitting use performance-based seismic design concept for that estimation. In that concept, various performance levels are associated with a limitation of the damage state with respect to a given earthquake. However, displacement limits are utilized for the damage state instead of computational damage measures.

The aim of this work is, therefore, to define explicit damage indices, which may be used as seismic design criteria for reinforced concrete frames. Such explicit damage criteria for design, assessment or retrofitting need mechanically well-founded damage measures, which are applicable both to individual members and entire structures.

Several damage indices for seismic assessment have previously been developed and are already well-known. A comprehensive overview can be found for example in [1, 2]. The damage indices giving quantitative information of the damage state can be local or global. A majority of the well-known damage indices usually refer to the local state of a cross-section or a structural member. Most of them are obtained from the ductility ratio or the stiffness ratio or the energy ratio defined within the moment-curvature relationship.

Only a few of the known damage indices are global, and they are usually empirical. Sometimes, they are even mechanically inconsistent, such as the combined index by [3] defined as a sum of a relative displacement and a relative energy measure. One of the consistent damage measures has been proposed by [4] for the finite element structural analysis and monotonic loading. Another consistent damage measure has been proposed in [5, 6] based on the reduction of structural stiffness. However, the structural stiffness is a multi-dimensional function and several difficulties appear by derivation of a scalar global damage index from a multi-dimensional functional.

Apparently, seismic design needs not only proper local damage indices, but also proper global ones. It is, however, hardly possible to define a global damage measure for all structural types and all structural materials such as reinforced concrete, steel and masonry. The objective of the present work is, therefore, to define proper local and global damage indices only for reinforced concrete structures. They shall vary between 0 (state without damage) and 1 (failure or collapse).

For the current study, the finite element program FRAME has been developed within the Matlab environment [7] using classical beam elements. In this program, elasto-plastic bilinear moment-curvature relationships are used for the nonlinear material model including hysteretic behaviour under cyclic and dynamic loading. The stiffness matrices of the elements are obtained by use of the spread plasticity model along the length. The Newmark-Beta method with constant average acceleration is applied for the step-by-step time integration of the governing equations. A variety of examples has been analysed by the program to check out the sensitivity of the global damage indices for reinforced concrete moment frames.

## 2 COMPUTATIONAL MODELS FOR MATERIAL AND MEMBER BEHAVIOUR

Both static (push-over) and dynamic nonlinear analysis procedures can be used in seismic design. The relevant nonlinear material and member models have to be defined for the nonlinear analysis. In the present work, the nonlinear material model of a reinforced concrete member is defined on the level of the moment-curvature relationship of its cross-section. For monotonic loading, the moment-curvature relationship can be defined as a piecewise linear diagram containing the characteristic points associated with the cracking, yielding and failure states of the member. However, the key issue in material modeling for cyclic and dynamic

loading is the hysteretic behaviour of the material. Several hysteretic models for reinforced concrete have been developed in the past. One of the well-known hysteretic models is the model by [8], which has been then modified by several authors. Such hysteretic models are usually empirical in nature. Another well-known model is the bilinear hysteresis model on the basis of the plasticity theory. Here, the bending stiffness during elastic loading and unloading is taken as the initial bending stiffness for the monotonic loading as shown in Fig.1. In the present work, this bilinear hysteresis model will be used for the seismic analysis and determination of the damage indices under cyclic and dynamic loading.

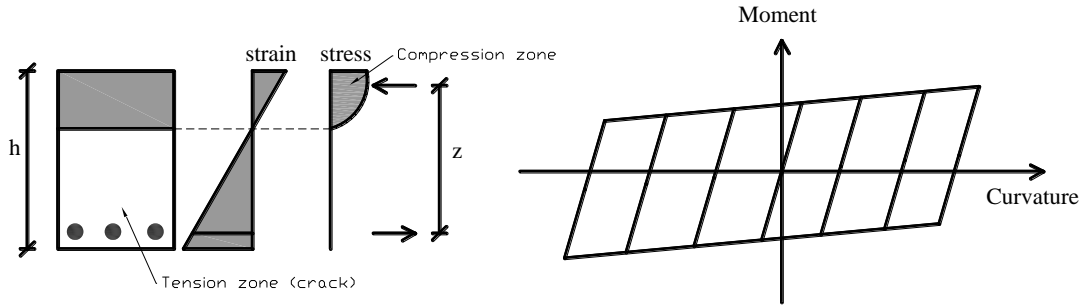


Figure 1: Material model.

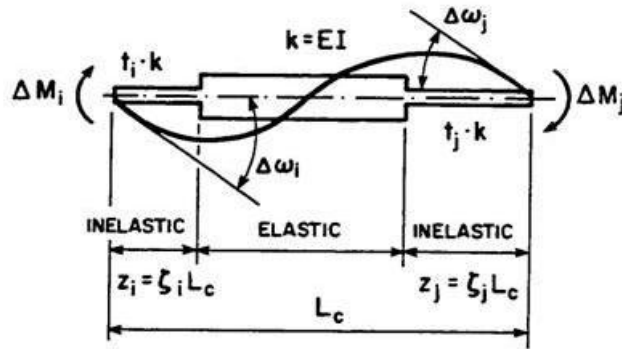


Figure 2: Member model.

The hysteretic models are usually defined for the cross-sections, but the bending stiffness of the member is needed for the analysis. Several member models for reinforced concrete have been developed until now. The member models are generally subdivided into one-component and multi- component models. In a multi-component model, the member consists of different parts acting in parallel. While one part behaves only elastically, the other behaves plastically. In a one-component model, the member consists of only one part which includes all the properties. In one variant of this model, the plasticity is assumed to occur only at the end of the member. However, it is more suitable, when plasticity is spread within the member. In this work, the spread plasticity model by [9] is used as shown at Fig.2.

### 3 COMPUTATIONAL DAMAGE MEASURE FOR SEISMIC LOADING

The damage in material is usually defined as softening of its stiffness and its extent can be quantified as the relative reduction of its actual modulus of elasticity ( $E_x$ ) with respect to an initial value in the non-damaged state ( $E_0$ ) and the critical value ( $E_f$ ) at failure:

$$D = \frac{E_0 - E_x}{E_0 - E_f} \quad (1)$$

The obvious advantage of this definition is a scalar damage index,  $D$ , ranging from 0 (no damage) to 1 (failure).

At the cross-section level, for example, at pure bending, the damage index can be derived in a similar way from the reduction of the bending stiffness  $EI$  of the beam elements:

$$D = \frac{(EI)_0 - (EI)_x}{(EI)_0 - (EI)_f} \quad (2)$$

However, these damage measures are local and it is a challenge to define a similar scalar global damage index for the entire structure. [5] showed that a scalar global damage index can be quantified by the reduction of the structural stiffness represented by some scalar characteristic values  $\lambda$ :

$$D = \frac{\lambda_0 - \lambda_x}{\lambda_0 - \lambda_f} \quad (3)$$

Nevertheless, the choice of  $\lambda$  characteristic values is a challenge. It is more suitable to define a damage index based on scalar deformation energy. [4] proposed to define a global damage index as the relative reduction of the whole structural deformation energy ( $W_p$ ) with respect to an initial value in the non-damaged state ( $W_p^0$ ):

$$D = \frac{W_p^0 - W_p}{W_p^0} = 1 - \frac{W_p}{W_p^0} \quad (4)$$

At that, the global damage index is a scalar varying between 0 (state without damage) and 1 (failure state). By use of the finite element simulation, this energy-based global damage index can be calculated from the actual displacement field as follows:

$$D = 1 - \frac{W_p}{W_p^0} = 1 - \frac{\sum_e \mathbf{a}^T \int_{V_e} \mathbf{B}^T \boldsymbol{\sigma} dV_e}{\sum_e \mathbf{a}^T \int_{V_e} \mathbf{B}^T \boldsymbol{\sigma}_0 dV_e} \quad (5)$$

where  $\mathbf{a}$  stands for the nodal displacement vector,  $\mathbf{B}$  for the strain shape matrix and  $V_e$  for the volume of each finite element  $e$ . Further,  $\boldsymbol{\sigma}$  denotes the actual stress vector and  $\boldsymbol{\sigma}_0$  the stress vector calculated for the undamaged material and the same global displacement  $\mathbf{a}$ . Herein, the total potential energy  $W_p$  as well as  $W_p^0$  is accumulated over all finite elements.

However, the local and global damage indices discussed above are suitable for the monotonic loading. They can be mainly used in the push-over analysis. Damage indices suitable for cyclic and dynamic analysis shall be properly defined. Several empirical local damage indices for cyclic or dynamic loading have previously been proposed. [10] proposed a theoretical local cyclic damage index by using the absorbed energy calculated from the moment-curvature relationship. At first, the damage indices for the positive and negative directions are separately calculated. Then, the cyclic local damage index is defined by their superposition as follows:

$$D = D^+ + D^- - D^+ D^- \quad (6)$$

This local damage index is defined on the cross-sectional level and cannot be used for the damage state of the whole structure. Nevertheless, the idea of defining two separate damage indices for positive and negative directions can be combined with the monotonic energy based global damage index [11]:

$$D_G^\pm = 1 - \frac{\sum_e (a^{(e)T} - a_0^{(e)T}) \cdot K_d^{\pm(e)T} \cdot (a^{(e)T} - a_0^{(e)T})}{\sum_e (a^{(e)T} - a_0^{(e)T}) \cdot K_0^{\pm(e)T} \cdot (a^{(e)T} - a_0^{(e)T})} \quad (7)$$

The cyclic or dynamic global damage index can be then obtained in a similar manner from the superposition of the two separate global damage indices:

$$D_G = D_G^+ + D_G^- - D_G^+ D_G^- \quad (8)$$

## 4 EXAMPLES

### 4.1 RC Column

The new proposed global cyclic damage measure is applied on a canti-lever reinforced concrete column which is originally tested by [12]. The column was subjected to horizontal cyclic loading. Its geometry, reinforcement and cross-sectional properties are shown in Fig. 3 and its material properties are given in Table 1.

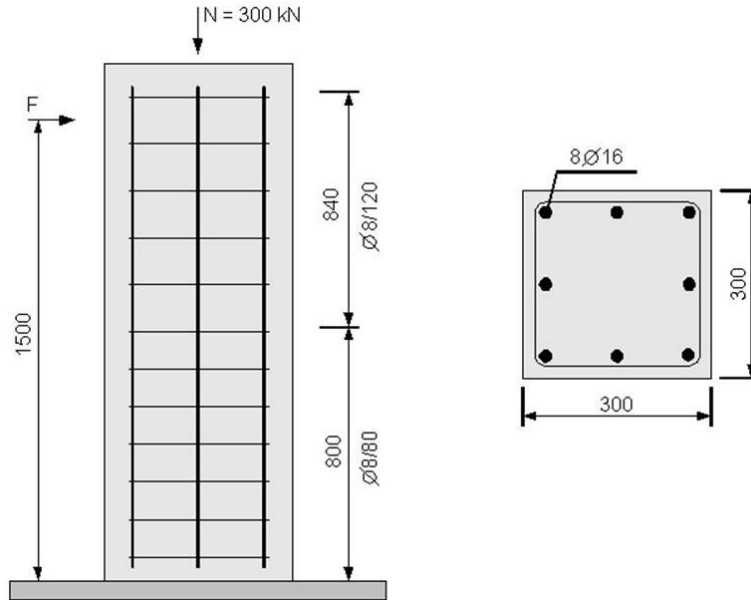


Figure 3: Geometry, cross-section and reinforcement of the RC column.

Concrete	Reinforcing steel
Young's modulus $E_c = 29634 \text{ M N/m}^2$ compressive strength $f_{cm} = 35,6 \text{ MN/m}^2$	Young's modulus $E = 201000 \text{ M N/m}^2$ yielding strength $f_y = 514 \text{ M N/m}^2$ ultimate strength $f_u = 593 \text{ M N/m}^2$ ultimate tensile strain $\epsilon_{su} = 0.0044$

Table 1: Material properties of the RC column

The moment-curvature diagram of the section at the base is given in the Fig. 4. It is in a good agreement with the bilinear hysteretic material model. It can be seen from the calculated force-displacement diagram of the upper corner that the obtained structural response correlates well with the experiment (Fig. 5). In Fig. 5, the variation of the cyclic global damage index is also shown. With each loading cycle, its value gradually increases and becomes close to 1 at failure, as expected.

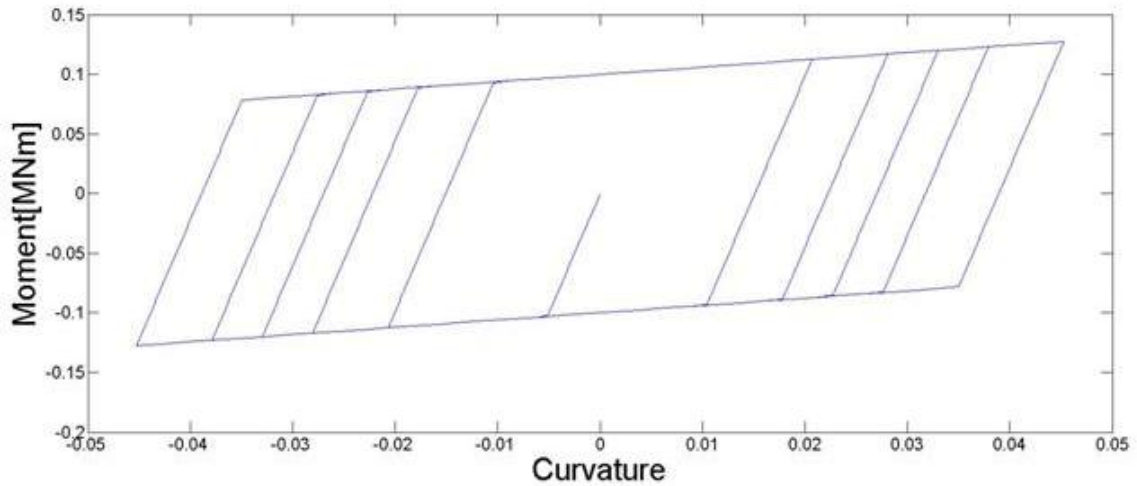


Figure 4: Moment-curvature relationship of the cross-section at the base of the RC column.

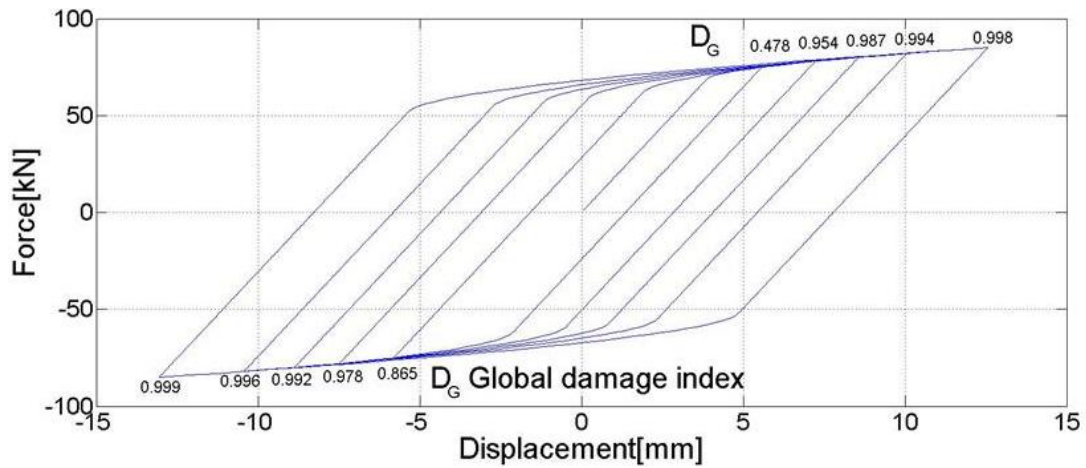


Figure 5: Force-horizontal displacement of the upper corner of the RC column.

### 4.2 Portal Frame

The new proposed global dynamic damage measure is applied on a reinforced concrete portal frame which is tested by [13]. The portal frame was subjected to a steady-state harmonic ground acceleration given in Fig. 8. Its geometry is given in Fig. 6 and its material properties in Table 2. The reinforcement and cross-sectional properties are shown in Fig. 7.

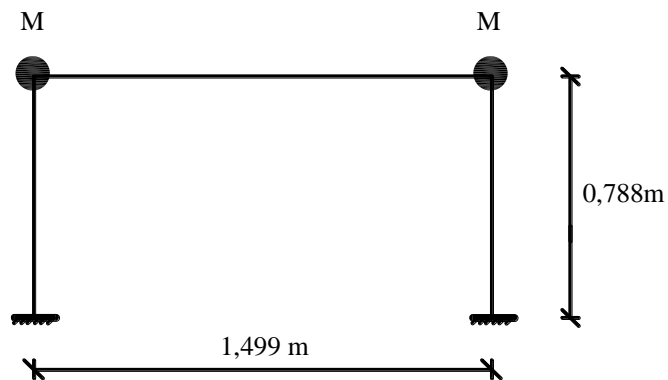


Figure 6: Geometry and mass distribution of the portal frame.

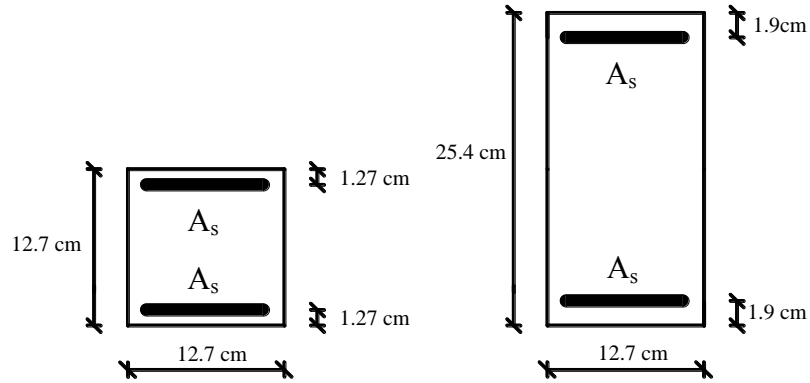


Figure 7: Reinforcement and cross-sections of the portal frame

$E_s= 199948 \text{ MN/m}^2$
$E_c= 21836 \text{ MN/m}^2$
$f_{sy}=351.63 \text{ MN/m}^2$
$f_{cy}= 32.75 \text{ MN/m}^2$
$M= 972 \text{ kg}$
$A_s= 1.43 \text{ cm}^2$

Table 2: Material properties of the portal frame.

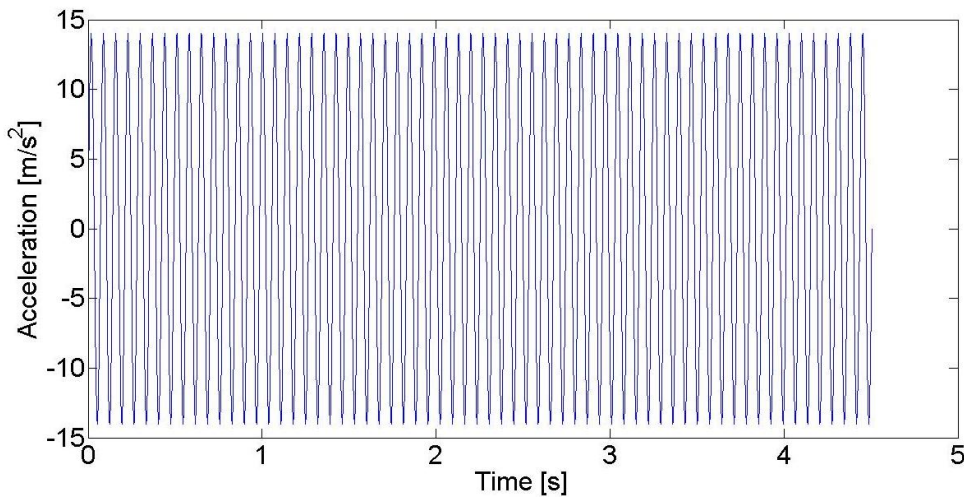


Figure 8: Base acceleration applied to the portal frame

The time-maximum horizontal displacement diagrams of the recorded and calculated response are shown in Fig.9 and 10 respectively. It can be seen from these diagrams that the obtained structural response correlates well with the experiment. In Fig. 11, the variation of the dynamic global damage index ( $D_G$ ) is also shown. During the first loading cycle, the value of  $D_G$  gradually increases. After the first loading phase it becomes 0.42 and after the loading in the opposite direction it increases rapidly to 0.69. During the following loading cycles the value of  $D_G$  increases firstly by a small amount then it remains constant as expected.

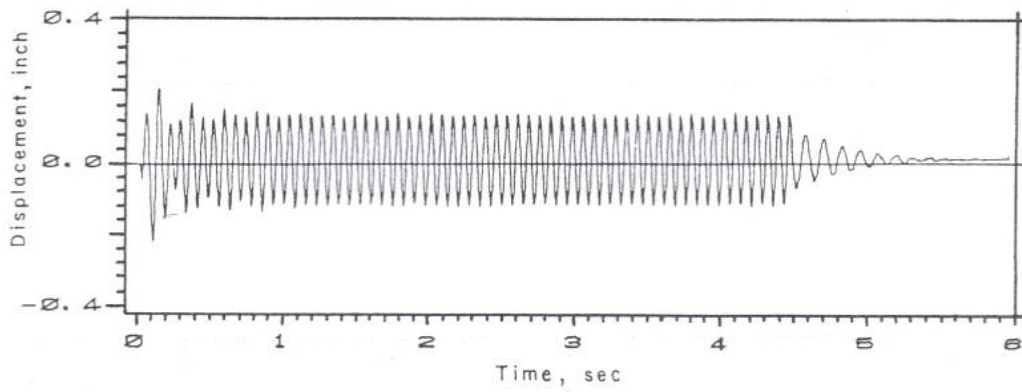


Figure 9: Recorded response.

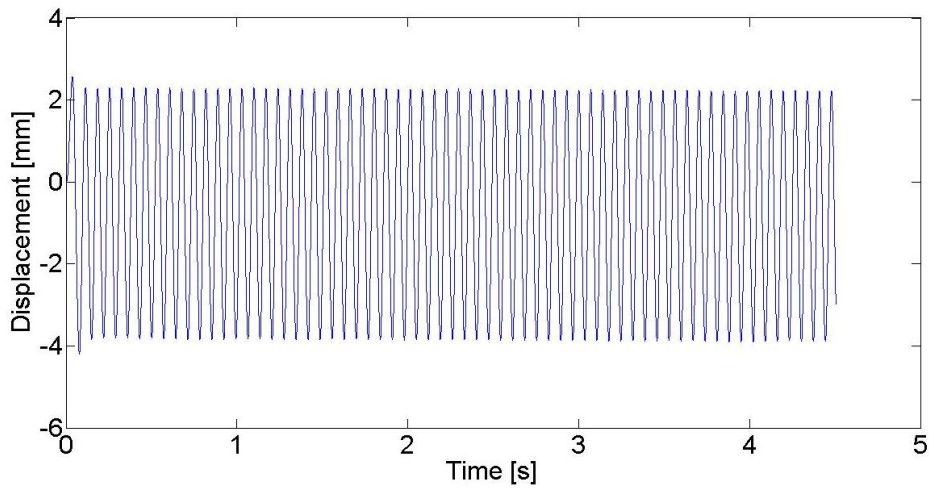


Figure 10: Calculated response.

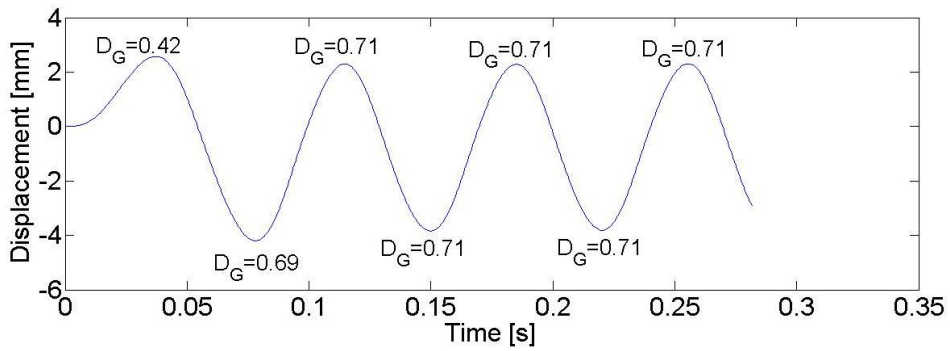


Figure 11: Displacement and global damage index under dynamic loading.



## 5 CONCLUSIONS

Damage measures for cyclic and dynamic loading have been proposed for reinforced concrete frames. These damage measures have been tested and compared to experiments. The proposed damage indices stand in a good agreement with the observed damage in experiments and provide a reliable damage measure for seismic design.

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