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DESIGN AND VERIFICATION OF A DYNAMIC EXPERIMENTAL CAMPAIGN ON ANCHORING SYSTEMS THROUGH MACRO AND MICRO NUMERICAL MODELS

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Abstract. *The seismic safety of non-structural elements especially in the case of relevant components on strategic structures, such as hospitals, fire and police stations as well as any further building for the emergency management, is often linked to the behaviour of connections with the structure [1-3].*

This paper presents the design of a dynamic experimental campaign on a whole structure on the basis of two different numerical simulations, an overall macro model and a detailed micro model. The whole experimental program involves the study of fasteners with different functioning principles, namely bond, expansion and undercut. The calibration of the numerical simulation of an anchoring system, among those considered in the laboratory campaign, is based on the results of tension and shear tests performed on the selected fastening.

This paper discusses both the design of this experimental campaign and the calibration of the local model for an anchor, comparing numerical and experimental results [4].

The first macro model considers the whole structure to be tested, in order to study the modification of the seismic input through the height of the specimen. This preliminary analysis is developed for all the considered fasteners. The design of masses, in terms of weight, is based on these global FE models. This numerical simulation is performed for all the considered anchoring systems. The second micro model, based on the results of the first one, analyses in detail the dynamic behaviour of a single anchor. The overall strength and the load-slipping behaviour is studied and compared with the experimental results. This micro model is based on a preliminary calibration obtained from quasi-static tests performed on the considered fastening system.

The comparison between numerical and experimental results confirms the good agreement of the predicted behaviour with that observed during the quasi static tests on a single anchor. This will also allow to extent the FE simulation to different loading conditions as well as to develop parametric studies for different applications, especially in the case of dynamic numerical analyses.

1 INTRODUCTION

The non-structural components normally present on buildings are those elements housed or fixed to the floors and walls such as suspended ceilings or facilities which do not contribute to the structural behaviour of the building [1]. These are generally complementary elements as electricity or mechanical devices, architectural equipment or building contents.

In case of a seismic event the non-structural components may be subject to large forces, transmitted to these elements by the anchors. Thus fastening systems should be designed to ensure the stability of the non-structural element in case of an earthquake. As an example, the collapse of a suspended ceiling or the overturning of a library represents a serious and relevant risk for the occupants of a building. Furthermore for strategic structures, such as hospitals or police or fire stations the operability of the building immediately after a seismic event should be guaranteed. In this sense the anchoring systems of non-structural elements should be designed in order to prevent the occurrence of damage to these components.

The purpose of the presented research is to predict the dynamic behaviour of different anchoring solutions, in order to design an experimental campaign aimed at verifying the strength and the failure mechanisms of some fastening methodologies. These analyses could be then compared with the experimental results [5].

2 TEST FRAME AND EXPERIMENTAL SETUP

The behaviour of different anchoring systems will be investigated by shaking table tests at the ENEA Research Center "la Casaccia" (National Agency for New Technologies, Energy and Sustainable Economic Development). The experimental campaign involves several steps for each testing setup. Anchors of different mechanical principles and with different overall strength are considered [6]. In particular three kinds of fastening methodologies are considered: expansion, undercut and bonded anchors (Figure 3).

A concrete structure was designed as a support frame [2] and this is constituted by four RC walls arranged with cross plan (Figure 4). On each concrete wall a couple of steel masses are hanged to the structure. Each of these is fixed with a single anchor in order to more easily study the overall strength and failure mechanisms of the considered fastening solution.

The input signal transmitted to the shake-table is generated according to AC156 [5].

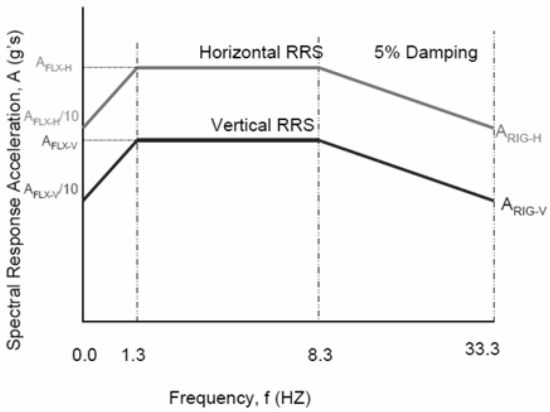

Figure 1: Required response spectrum, normalized for the component [5].

This standard imposes detailed limits to be met on both the frequency content of the signal and its elastic response spectrum. In particular, the signal should have a frequency content between 1.3Hz and 33.3Hz, a duration of at least 30s of which 20s of strong motion and an envelope profile build-hold-decay. On the basis of these parameters a dynamic signal in compliance with the operating limits of the shake-table should be generated. In this sense the limits are a maximum displacement of 0.25m, a maximum velocity of 0.5m/s and a maximum acceleration related to the maximum overturning moment of 300kNm.

To generate the input and to comply with all these requirements a synthetic signal has been generated through the SIMQKE code [7]. Subsequently a band-pass filter between 0.6Hz and 33.3Hz and a spectrum matching procedure with addition of wavelets were applied to correct both the frequency content and the spectrum of generated signal [8]. The input was finally scaled to obtain the signals for the different runs of the test with increasing intensity.

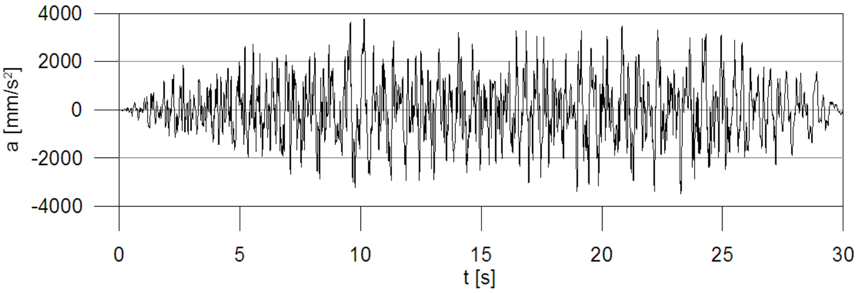

Figure 2: Acceleration time history in direction x with ZPA = 0.4 g.

For each session of tests several ground motions at increasing levels of ZPA (Zero Period Acceleration, as presented on [5]) were applied. This procedure will also allow to study the dynamic behaviour of non-structural elements installed at different floor levels if the floor spectra are considered on the analyses [9].

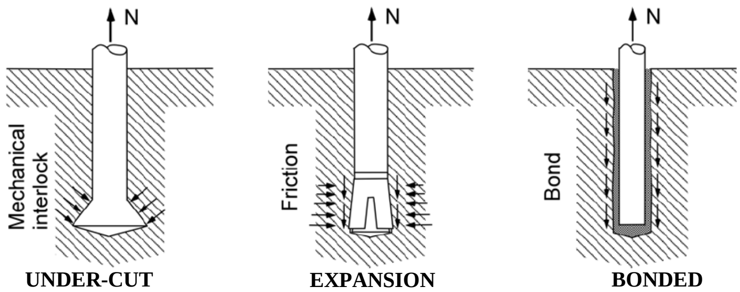

Figure 3: Different types of anchoring systems.

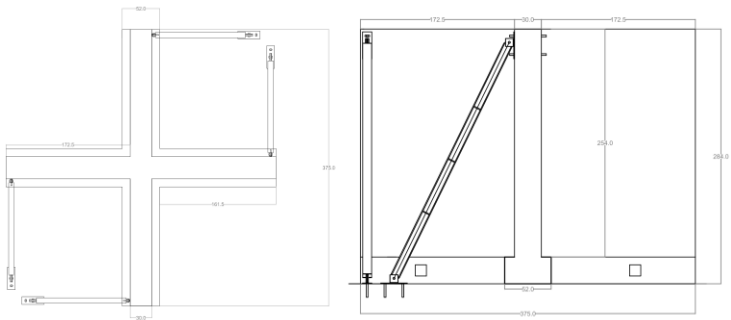

Figure 4: Design of the concrete structure.

The design of the experimental campaign was performed on the basis of two different numerical analyses. A first model of the whole structure has been used to calibrate the entity of the masses to be hanged and to study the variation of stress on the anchors increasing the intensity of the seismic input. The second model has been used to study in detail the overall behaviour of an anchoring system. In particular an expansion fastening system with plastic sleeve was considered.

3 MACRO MODELLING

3.1 Description of the Model

The use of a finite element model in order to predict the behaviour of the testing frame has imposed the need to preliminarily evaluate the reliability of the model itself [3, 10]. For this purpose, different numerical simulations with a gradually increasing complexity were developed to obtain the final model, used to design the structure considered in the experimental campaign. All the numerical analyses were performed using the software Straus7 [11]. This process allowed the reliability of the more basic models to be verified comparing the obtained results in terms of frequencies and mode shapes. The most important features of the structure are essentially the natural frequencies of vibration and the vibration modes that depends on the stiffness of the frame [6 9]. The four considered models are presented on figures from Figure 5 to Figure 8 respectively and they are characterized by an increasing complexity.

The complete FE model consists of 3608 plates to represent the walls and 4 truss elements to simulate the influence of braces. Each steel element, fixed to the structure through the selected anchors, is modelled using a nodes with an assigned mass, positioned in the centre of gravity of the steel block, and 8 beam elements to connect these nodal masses with the surface of the support. The beam elements have been preferred to the link elements since a well calibrated stiffness do not affect the behaviour of the structure and it allows the stress in the connected nodes to be investigated.

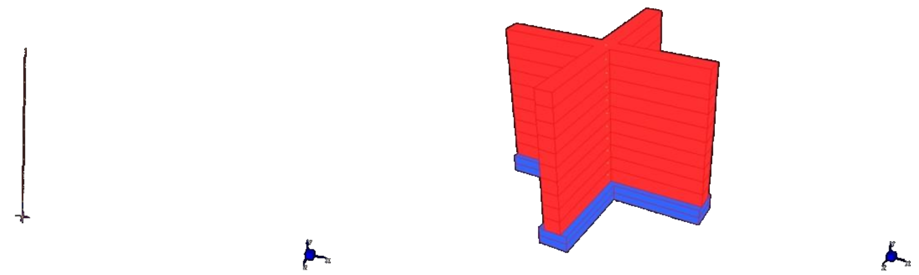

Figure 5: Single beam model, wireframe and solid views.

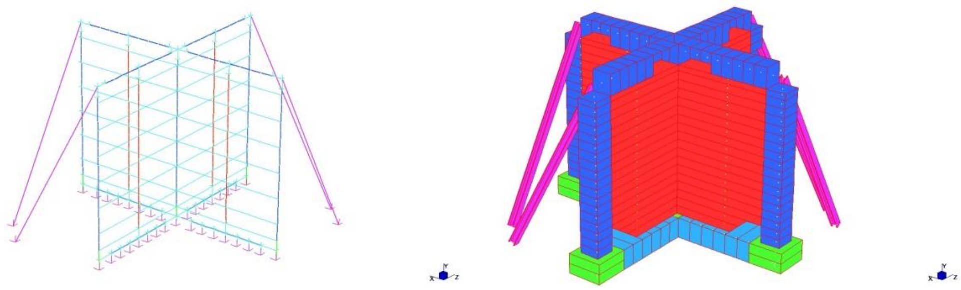

Figure 6: Multi beams model, wireframe and solid views.

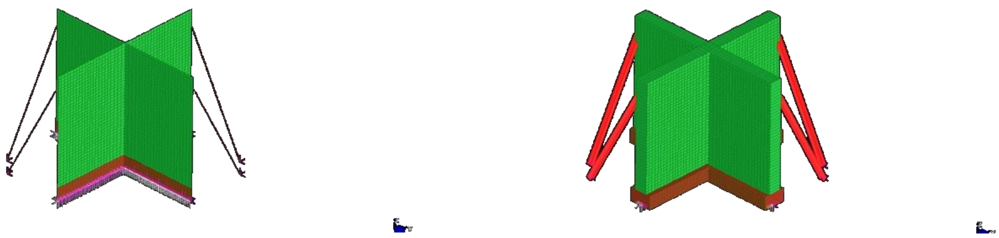

Figure 7: Plate model, wireframe and solid views.

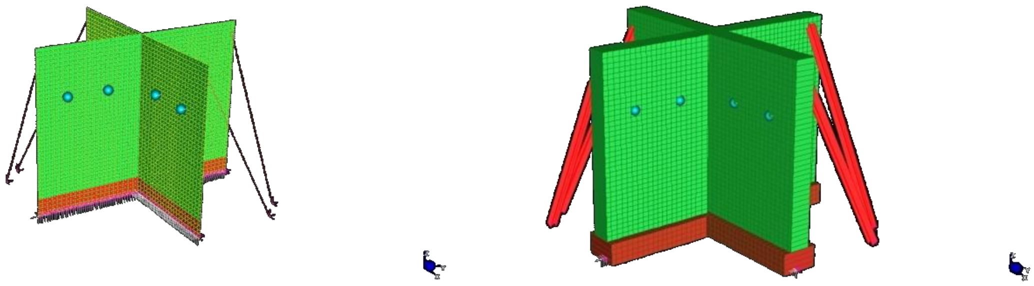

Figure 8: Plate model with adjunctive masses, wireframe and solid views.

3.2 Numerical Results

The first three models were considered to determine the stiffness of the structure. As Table 1 shows, the natural frequencies obtained from different numerical analyses are very close to each other. In this sense the more refined numerical simulation shows overall characteristics, especially in terms of stiffness, similar to those of the less complex models, so this was used for the subsequent analyses.

Mode	Single Beam Model [Hz]	Beam Model [Hz]	Plate Model [Hz]
1	35.34	58.13	59.61
2	105.19	75.49	75.38
3	125.49	77.62	78.50
4	125.49	78.89	81.01

Table 1: natural frequencies of different macro models.

The first design phase of the experimental campaign aimed at calibrating the values of mass to be anchored on the structure. This allowed the stress of the fastening systems to be maximized in compliance with the operating limits of the shaking table. The first considered approach was to fix the mass value for each anchor and to determine the maximum achievable level of acceleration. The computed load acting on each block was compared to the related anchor resistance, under dynamic conditions. These data allowed the verification of the fastening systems through the following normalized formulation:

$$F_{eq,adim} = \frac{N_{tot}}{N_R} + \frac{T_{xz}}{T_R} + \frac{T_{xy}}{T_R} \tag{1}$$

where:

- N_{tot} is the total axial force, which is the sum of: $N_{tot} = N + \frac{M_{xz}}{b_{xz}} + \frac{M_{xy}}{b_{xy}}$ with M_{xz} and M_{xy} principal moments, and b_{xz} e b_{xy} distances between the anchor and the contact point of steel block with the wall in horizontal and vertical directions;
- T_{xz} is the shear force acting on the x-z plane;
- T_{xy} is the shear force acting on the x-y plane;
- N_R is the tensile resistance for dynamic loading;
- T_R is the shear resistance for dynamic loading.

The second procedure considers the maximization of the load acting on the anchor increasing the hanged mass and allowing a reduction of the maximum attained acceleration. Comparing the results obtained from the various tests, the second approach has provided the best result.

Table 2 summarizes the value of hanged masses depending on each anchor type. The corresponding maximum normalized stresses are presented on the last column.

When the factor $F_{eq,\ adim}$, computed as presented on equation (1), attains the unit the maximum resistance in the element is achieved thus this corresponds to its failure. The maximum normalized stress on anchors of different types, evaluated with the global model, results less than the resistance. However this simplified model neglects some details to contain the computational effort of the FE models. In this case the strength of the anchoring systems was estimated applying an appropriate reduction factor to the static resistance. On these bases the anchors can be supposed to be failed also for ratios lower than the unit. In this sense the results presented on table 2 can be considered to identify the failure of the fastenings.

Subsequently to the calibration of the anchored masses, all testing steps have been numerically simulated considering increasing levels of ZPA. As an example, Figure 9 shows the results obtained for a plastic expansion anchor for a ZPA equal to 0.9 g (Figure 2).

Furthermore, this model allowed to study the effective seismic signal acting on each anchor. Indeed the structure filters the dynamic input and this could induce some modifications on the dynamic properties of the selected time history.

Anchor Typology	Steel Plate [kg]	$F_{eq,adim}$ [-]
Expansion (plastic)	300	0.98
Under-cut	500	0.75
Expansion (metallic)	700	0.86
Bond	900	0.90

Table 2: values of masses fixed to the structure and normalized load-strength ratios.

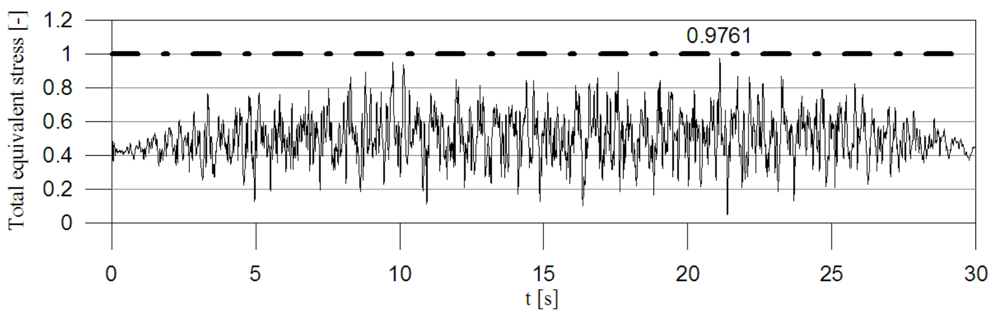

Figure 9: Total equivalent stress in the plastic expansion anchor for a test with a ZPA of 0.9 g.

4 MICRO MODELLING

4.1 Description of the Model

The local model was used to deepening the overall behaviour of an anchor system on the basis of the dynamic load actions computed using the macro model. This also allowed the hypothesis of reduction of the static resistance due to dynamic effects [4] to be validated.

The plastic expansion anchor was modelled using the software DIANA [12]. In particular the local model (Figure 10) consists of four parts: (1) a cube with the sides 10cm long to reproduce the concrete support; (2) a cylindrical hollow element to simulate the plastic sleeve; (3) a cylindrical component to model the screw; a set of 4 trusses to reproduce the overall behaviour of the steel block anchored to the testing frame.

In order to better modelling the behaviour of the whole fastening system subjected to both tensile and shear loads, two interfacial surfaces were inserted: one between the concrete and the plastic anchor and the other one between the plastic anchor and the central element reproducing the screw (Figure 11).

The concrete was modelled using the Modified Maekawa Concrete Model, while the screw was modelled using a Von-Mises criterion to define the yield surface of steel's behaviour.

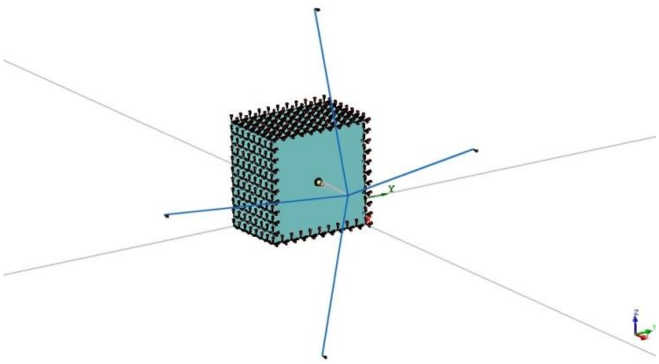

Figure 10: Detail of the adopted micro model.

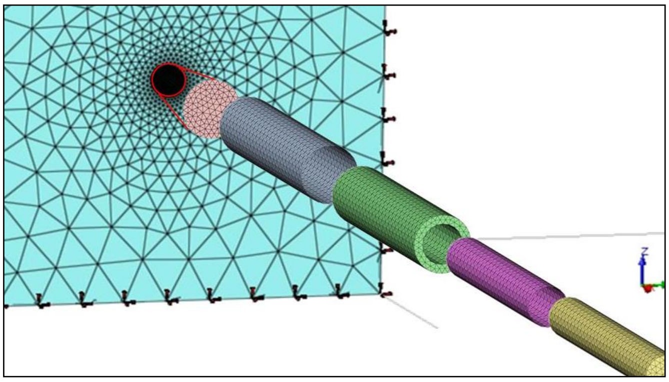

Figure 11: Micro model exploded view.

4.2 Calibration of Interface Elements

The behaviour of the whole fastening system subjected to extraction forces has been reproduced calibrating the stiffness of the plastic anchor assuming invalid the effects of mutual sliding and simulating this through the accumulation of plastic deformation in the external hollow element that represents the sleeve.

The overall behaviour of the fastening system subjected to both tensile and shear actions have been reproduced by calibrating the stiffness values of the material used for the sleeve. This calibration was based on the results of quasi-static tests (Figure 12).

Any specific constitutive model for plastic elements could not be found, thus the Modified Maekawa Concrete Model was applied. This allowed a non-linear behaviour with softening and plastic deformation to be defined. The principal parameters are presented in

Table 3.

Parameter	Unit	Value
Compressive strength	[N/mm^2]	16.00
Tensile strength	[N/mm^2]	3.96
Fracture energy	[N/mm]	1.00
Shear retention	[-]	0.20

Table 3: parameters used to perform the Modified Maekawa Concrete Model.

The results obtained from the proposed model show a good agreement with the experimental measures in terms of both tensile and shear loads.

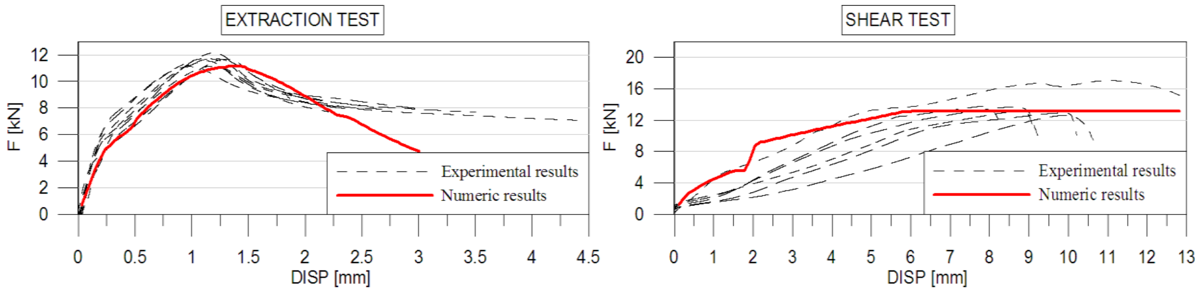

Figure 12: Calibration of micro model, numeric and experimental results.

4.3 Numerical Results

The two target-contacter surfaces were specifically inserted to simulate the progressive increasing of the shear stiffness with the crushing of the plastic anchor. This interface also guarantees the respect for the geometric limits, namely when the screw comes into contact with the support and its deformation is concentrated outside the support (Figure 13).

The calibrated mechanical law for the interface elements was included into the micro model. The acceleration time history obtained from the macro model at the exact point of application of the fastening system was then applied as input on this local numerical simulation. Figure 14 shows the results obtained for the most strong seismic input, also taking into account the effects of previous load steps.

The obtained results confirm as the dynamic analysis provides a much more heavy stress in the anchor if compared with that computed on the global model, that is based on a linear analysis. On the actual numerical analysis the failure is attained at 8.1s of the seismic input and this confirms the reliability of the considered assumptions.

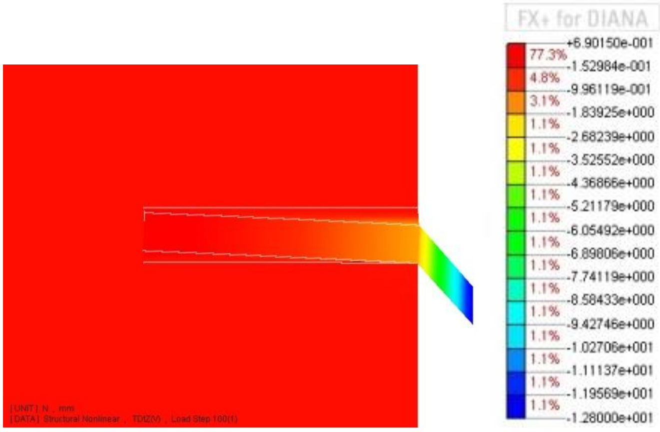

Figure 13: Shear failure of micro model, strain in "z" direction.

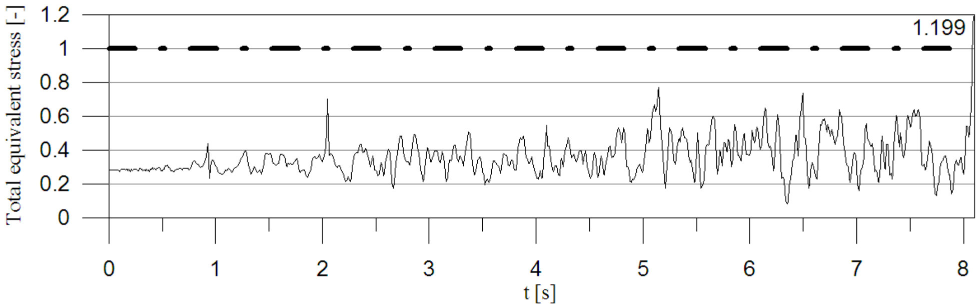

Figure 14: Micro model, simulation of run with a ZPA of 0.9 g.

5 CONCLUSIONS

The paper presents a series of numerical analyses characterized by an increasing complexity and by more refined results. On these bases an experimental campaign could be designed considering both the limits of the laboratory facilities and the mechanical characteristics of the selected anchoring methodologies.

Different macro models aimed at simulating the overall behaviour of a concrete structure upon which 8 steel masses are fixed with four different anchoring systems. These FE models allowed the calibration of the mass levels to be considered in the experimental program. Furthermore these analyses allowed to study the modification of the input signal from the base of the structure up to the fastening point, highlighting as any significant variation can be observed.

A second phase considered a micro model focused on a detailed numerical analysis of a single anchor. A preliminary calibration allowed the overall behaviour of the considered fastening solution to be reproduced by a FE simulation. The comparison of these numerical and experimental results in terms of the load-displacement curve confirmed the reliability of developed studies.

The dynamic input obtained from the macro model could then be considered as the input for the micro model, thus allowing the overall behaviour of the considered fastening solution to be studied in terms of load and displacement capacity. This second step of analysis allowed in particular to study the seismic level that induces the failure on the analysed anchor.

Finally the adopted overall process of analysis that considers two steps, a series of global models with increasing complexity and a refined local simulation, allows on one hand to limit the computational cost of the numerical study and on the other hand to obtain detailed results.

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