The Effect of the Number of Response Cycles on the Behaviour of Reinforced Concrete Elements Subject to Cyclic Loading

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SUMMARY:
The development of damage in reinforced concrete (RC) structures is a cumulative process. Some damage indices used to quantify damage make use of the number of response cycles as an Engineering Demand Parameter (EDP) relating with damage development. Other indices make use of deformation in terms of displacement or chord rotation. These functions are generally a function of whether the response is monotonic or cyclic, and are insensitive to the number of major deflection cycles leading to that state of damage. Many such relations are derived from experimental data from low-cycle fatigue tests performed on RC elements. The loading in such tests generally consists of either a monotonic increase in load or a gradually increasing cyclic load. Since damage development is a cumulative process, and hence depends on the load history, the loading pattern in low-cycle fatigue tests for assessment purposes should reflect the response of an earthquake. This paper will discuss a procedure to determine a loading history for cyclic tests, based on earthquake demands. The preliminary results of a campaign of low-cycle fatigue tests on RC elements to investigate the effect of using different load histories are also discussed.

Keywords: Low-cycle fatigue tests; Loading history; Seismic assessment; Reinforced concrete structures.

1. INTRODUCTION

The development of damage in reinforced concrete (RC) elements due to earthquake loading is a cumulative process, which depends on the load excursion path, sequence of cycles, the number of cycles and the relative amplitude of each cycle (FEMA 461, 2007). Despite this, the cyclic nature of earthquake loading is only partially taken into account in existing damage indices because, in a predictive sense, it is not possible to know the earthquake excitation a priori. Where it is taken into account, there are differences in opinion as to which cycles contribute to the achievement of different levels of damage. For example, Panagiotakos et al. (2001) observes that the ultimate chord rotation of an RC element does not depend on the exact number of equivalent cycles it is subjected to before ultimate-limit-state but only on the number of cycles having the maximum displacement. Krawlinker (1996) instead indicates that the excursions occurring before the peak cause most of the damage. Figure 1 compares two similar specimens tested with different load histories (Takemura et al., 1997). In this case, it is evident that failure occurs at a lower value of drift when a larger number of loading cycles is employed.

Most formulations of engineering demand parameters and damage indices, are calibrated with experiments on RC structures or components. Reference is generally made to three types of experiments. In shaking-table experiments, the input loading simulates a real earthquake and the response of the structure and its component is similar to that of a real event. In hybrid testing, the input loading is a response history that is derived from the response of the whole structure to a simulated earthquake event. In the case of low-cycle fatigue tests, the input cyclic load pattern is a response history, which is generally not directly related to an earthquake. However, most of the damage indices and engineering demand parameter formulations found in literature refer to data obtained from the latter type of experiments.

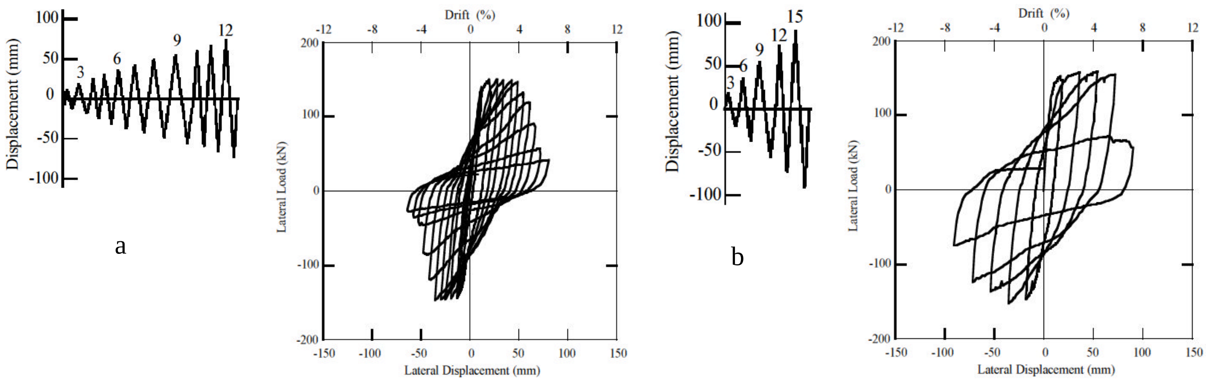

Figure 1. Low cycle fatigue tests on piers, using different cyclic loading histories (Takemura et al., 1997)

This paper describes a procedure for determining the loading history for a low-cycle fatigue testing campaign for the assessment of RC column elements (Borg et. al., 2012). The proposed new loading history is adopted together with other standard loading patterns in low cycle fatigue tests on RC columns to investigate the effects of the load path and number of cycles on the behaviour of RC column elements. The preliminary results are presented.

2. LOADING HISTORY FOR A LOW-CYCLE FATIGUE TESTING CAMPAIGN

2.1. Methodologies and Loading History Patterns

Krawlinker (1996) suggests that the criteria for selection of a loading history should be based on a maximisation of the information, and minimisation of complexities that make it difficult to give a universal interpretation of the results. The loading history should incorporate all relevant cycles and must ensure that all the energy demands are input to the testing system. The choice of the loading history also depends on the purpose of the experiment and the type of failure mode (Krawlinker, 1996). Low-cycle fatigue tests are popular for the calibration of numerical procedures where the demands are generally different from cases when the experiments are carried out for assessment purposes. In the former, a larger number of cycles is typically required. There are various loading history patterns found in literature. A frequently used loading history, which is also suggested by Krawlinker (1996) and adopted in FEMA 461 (2007), is shown in Figure 2a.

In order to evaluate modes of failure in RC elements FEMA 461 (2007) suggests the following procedure for defining the experimental loading history (Figure 2b):

1. Conduct a monotonic test to identify the ultimate displacement (Δ_u) or the displacement at the relevant damage state. The first amplitude is taken at $\Delta_1 = \Delta_u/10$.
2. Define the first stage of the loading history by providing 10 cycles with amplitude of Δ_1.
3. For the next stages, the deformation amplitude should be increased by 20%, and 3 cycles are applied per stage.

FEMA 461 (2007) also remarks that damage effects at all damage states can be represented when a single loading history is used that is based in part on the evaluation of seismic response data and in part from judgement. This can be done by considering a loading response sequence where not all the excursions are assumed to occur before the maximum excursion, in order not to overestimate the damage at a particular damage level. The following procedure is therefore suggested by FEMA 461 (2007) for the definition of a loading history for use in low-cycle fatigue tests aimed at the study of damage development:

1. Carry out a time history analysis of representative structure using a number of selected accelerograms
2. Rearrange the response using a cycle counting procedure, by assuming all cycles occur before

the peak.
3. Normalise the analytical response history about its maximum excursion
4. Scale and adapt the loading history for the displacement or drift values required for the experiment.

This procedure is more consistent with the representation of earthquake response. It is used as the basis of the loading history determination procedure proposed here.

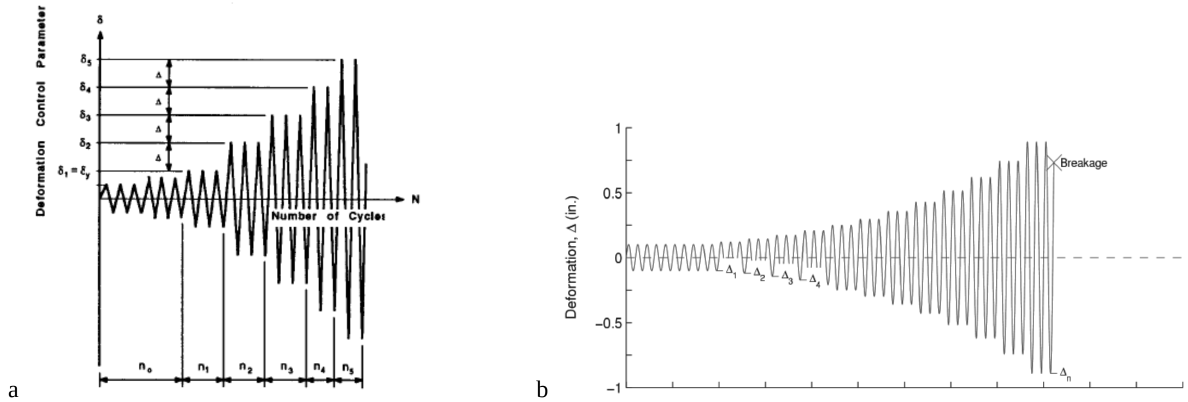

Figure 2. (a) Loading history as suggested by Krawlinker (1996)
(b) Loading history as modified by FEMA 461 (2007).

2.2 Proposed Loading History for Low-Cycle Fatigue Tests on RC Columns

Within this paper a loading history is derived and applied in a number of low-cycle fatigue tests on a range of RC columns with various reinforcement detailing described in Borg et al., 2012. The columns are designed to represent a variation in ground-storey columns in a typical non-seismically designed European RC frame structure (Figure 3, see also Borg, et al., 2012).

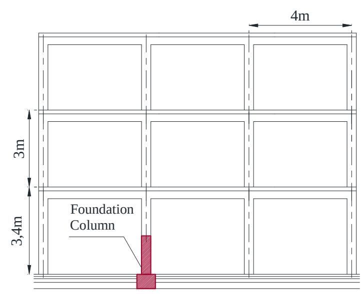

Figure 3. Reference RC frame structure

In order to derive an appropriate loading history, the procedure set out in FEMA 461 (2007) is modified as follows:
1. Select suites of accelerograms for various damage performance levels,
2. Conduct a monotonic test on a general RC column specimen
3. Calibrate the elements and material properties of a numerical model of the reference structure using the results of the monotonic test.
4. Carry out a time-history analysis of the reference structure using the selected suites of accelerograms.
5. Normalise the analytical response history about the yield excursion or point.
6. Count and re-order the cycles of the deformation response of the ground storey columns using the rain-flow counting method (ASTM E 1049, 2005) to obtain the required loading history.
7. Scale and adapt the loading history for the displacement or drift values required for the experiment.

Each stage of the process is described in further detail in the following sections.

2.2.1 Selection of accelerograms

Three earthquake hazard levels were considered: 100, 475, and 2475 year return periods, corresponding to operational, life safety and collapse performance criteria, respectively. For each hazard level, a suite of 7 accelerograms was selected (EN1998-1, 2004). The selection of accelerograms was made with the aid of REXEL (Iervolino et al., 2010) and is based on spectral matching of the average spectrum of the suite of records with the target spectrum for each earthquake hazard level. The elastic spectra of Eurocode 8 are adopted as target spectra. A lower and an upper bound divergence of 10% and 30%, respectively, were allowed between structural period values of 0.15s and 1.7s (Figure 4). However, in order to ensure this level of spectral matching, scaling of accelerograms was required. Hancock et al., (2007) indicate that spectrally matched accelerograms with considerable scaling factors may not cause any bias to non-linear response. Similarly, Bojorquez et al. (2011) indicate that the correlation between spectral shape and damage is not affected by the scaling factor applied to the accelerogram. Nevertheless, to minimise the effects of any controversy implied by scaling factors on soil characteristics, the structure was assumed to be on rock ground and the selected accelerograms were retrieved from rock ground conditions. For each earthquake hazard level in turn, checks are made to ensure the selected record durations are consistent with the typical earthquake magnitudes associated with the hazard level. This check was based on the significant duration, as this has a high correlation with the cyclic content of the time history that may have an effect on the response of the structure. Selection of accelerograms from near fault records was also ignored.

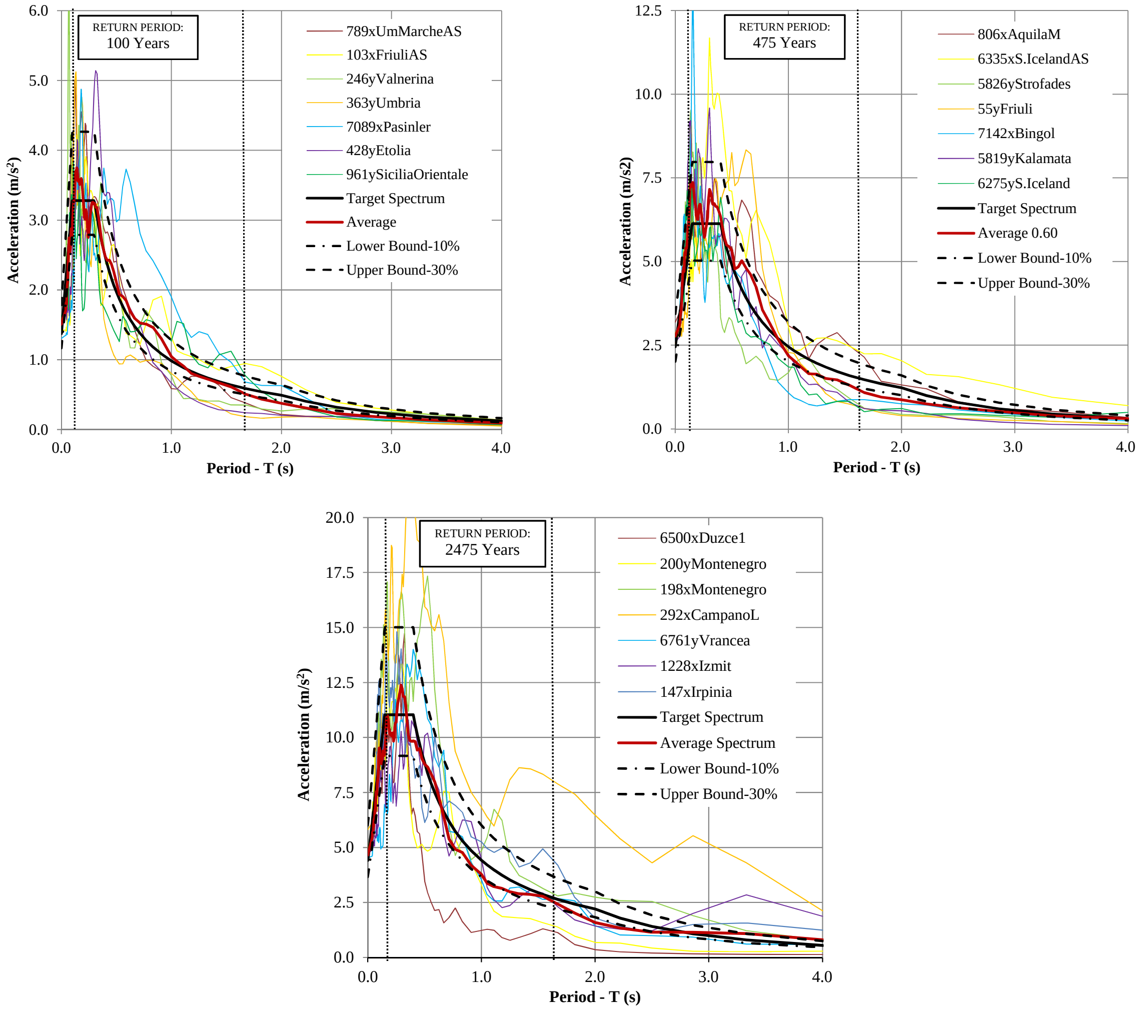

Figure 4. Spectral matching of the selected accelerograms for each earthquake level.

Table 1. Selected accelerograms for the time-history analysis.

Record ID	*Earthquake ID*	*Station ID*	*Earthquake Name*	*Date*	*Fault Mechanism*	*Mw*	*Epicentral Distance (km)*	*PGA (m/s^2)*	*Scale factor*	*Np*	*Bracketed Duration*	*Significant Duration 95% AI*	*Significant Duration 75%AI*
RETURN PERIOD: 100 years													
789x	355	ST225	Umbria Marche A.S.	12/10/1997	oblique	5.2	22	0.25	6.57	0.5	19.3	8.81	2.45
103x	28	SRC0	Friuli A.S.	15/09/1976	Thrust	5.9	16	1.29	1.1	0.74	27.93	8.72	5.27
246y	115	ST61	Valnerina	19/09/1979	normal	5.8	22	0.87	1.71	0.57	22.47	9.04	5.59
363y	174	ST138	Umbria	29/04/1984	normal	5.6	27	1.85	0.85	0.8	10.81	4.4	1.31
7089x	2290	ST557	Pasinler	10/07/2001	strike slip	5.4	32	0.19	6.81	0.63	32.31	11.01	6.13
428y	203	ST169	Etolia	18/05/1988	thrust	5.3	23	1.73	0.88	0.5	25.14	15.89	5.53
961y	424	ST297	Sicilia Orientale	13/12/1990	strike slip	5.6	51	0.89	1.84	0.83	31.77	20	8.33
					AVERAGE:	*5.5*	*28*	*1.01*	*2.82*	*0.65*	*24.2*	*11.1*	*4.9*
RETURN PERIOD: 475 years													
806x	178	FMG	Aquila	06/04/2009	Normal	6.3	19	0.26	12.1	0.63	42.00	22.03	10.26
6335x	2142	ST2557	S. Iceland A.S.	21/06/2000	strike slip	6.4	15	1.25	2.29	0.69	17.23	5.33	2.97
5826y	1887	ST1323	Strofades	18/11/1997	oblique	6.6	90	0.72	3.81	0.69	32.66	12.02	6.88
55y	34	ST20	Friuli	06/05/1976	thrust	6.5	23	3.10	0.83	0.73	25.23	5.22	2.52
7142x	2309	ST539	Bingol	01/05/2003	strike slip	6.3	14	5.05	0.53	0.44	23.88	4.56	3.17
5819y	1885	ST1321	Kalamata	13/10/1997	thrust	6.4	48	1.15	2.26	0.68	47.68	17.69	8.77
6275y	1635	ST2492	South Iceland	17/06/2000	strike slip	6.5	72	0.45	6.18	0.62	34.16	17.54	10.66
					AVERAGE:	*6.4*	*40*	*1.71*	*4.00*	*0.64*	*31.8*	*12.1*	*6.5*
RETURN PERIOD: 2475 years													
200y	93	ST68	Montenegro	15/04/1979	thrust	6.9	65	2.51	1.95	0.80	36.31	12.19	5.23
198x	93	ST64	Montenegro	15/04/1979	thrust	6.9	21	1.77	2.66	0.42	35.6	12.23	7.65
292x	146	ST98	Campano Lucano	23/11/1980	normal	6.9	25	0.59	7.68	0.58	66.26	40.34	15.28
1228x	472	ST561	Izmit	17/08/1999	strike slip	7.6	47	2.33	2.00	0.51	38.58	29.52	5.82
6500x	497	ST3136	Duzce 1	12/11/1999	oblique	7.2	23	4.86	0.98	0.82	26.81	13.16	10.06
6761y	2222	ST40	Vrancea	30/08/1986	thrust	7.2	49	1.41	3.21	0.49	16.66	9.53	6.16
147x	46	ALT	Irpinia	23/11/1980	normal	6.9	24	0.56	8.01	0.78	63.115	39.775	15.01
					AVERAGE:	*7.1*	*36*	*2.01*	*3.78*	*0.63*	*40.5*	*22.4*	*9.3*

2.2.2 Time history analysis of the reference structures

The numerical analysis was carried out using Seismostruct (Seismosoft, 2011). This is a fibre-based, Finite Element package. Figure 2 and element T14 in Figure 7 show the geometry and the cross-section details of the reference RC structure. A damping factor of 2% was applied. When compared to the traditionally adopted 5% damping, a 2% ensures about 15% more excursions (FEMA461, 2007). Since low-cycle fatigue tests are considered, strain rate effects are not simulated. Hence, numerical modelling aspects in this regard are also ignored. The modified model proposed by Menegotto and Pinto (1973) was adopted for steel, while the model for confined concrete was based on Mander et al. (1988). The ultimate strength of concrete (f_{cm}) was taken as 19MPa, the tensile strength (f_{ct}) 2MPa, and the yield strength of 12mm steel bars (f_{yk}) 416MPa. These values were based on specific tests carried out on the materials (Borg, et al., 2012). For each time history analysis corresponding to each accelerogram, the deformation response of the foundation column was obtained.

2.2.3 Counting of deformation cycles

There are various ways to count the deformation response cycles. In level-crossing counting deformation limits are set on the deformation history, and a count is taken each time the slope between a peak and a valley is exceeded. In peak counting, levels are defined in terms of deformation amplitude, and a count is considered every time this deformation amplitude is exceeded. In simple range counting, a range or a count is considered as the difference between two successive reversals. In rain-flow counting, the count is based on the size of the difference between a valley and a peak, and its sequence of occurrence, such that Miner's fatigue rules are conserved (ASTM E 1049, 2005). A seismic deformation response of a column is characterised by oscillations with large variations in amplitude. Level crossing counting, peak counting and range counting may result in an overestimate count of significant cycles, as small reversals are counted as full cycles. Furthermore, in these three counting processes, no reference is made to the sequence of excursions. Rain-flow counting is based on the sequence of excursions and size computed as the difference between a peak and a valley. Hence, a more realistic significant number of cycles is provided. As discussed in the next section, a simplified rain-flow counting method and the peak counting method are combined for the counting of response deformation cycles. Each deformation response from the time history analysis is reduced in a series of valley and peak points. In order to reduce the number of insignificant cycles, peaks and valleys which are less than 0.1% drift are filtered off.

2.2.4 The proposed loading history scheme

FEMA 461 (2007) suggests that the maximum excursion of the response should be normalised with the ultimate deformation of the monotonic tests. Panagiotakos et al., (2001) indicates that the ultimate deformation is not the same for monotonic and cyclic tests. Normalising the excursion values with the ultimate deformation therefore results in an overestimation of the number of cycles. It is here suggested that normalisation be carried out with respect to the yield deformation. The deformation capacity at yield is expected to be similar for both monotonic and cyclic loading situations. Furthermore, the here proposed procedure for determining a low-cycle fatigue load history adopts numerical analysis of the structure. In numerical modelling, the yield limit states are better defined than ultimate limit states. This is so due to the uncertainties associated with the definition of materials and modelling aspects at the ultimate limit state.

Using the counting techniques discussed in the previous section, three sets of loading histories are computed. In the first set (Figure 5a), the average number of cycles, are arranged in ascending order based on the deformation size, for each set of accelerograms. The re-ordering of cycles did not take into account the position of the formation of yield or the ultimate position.

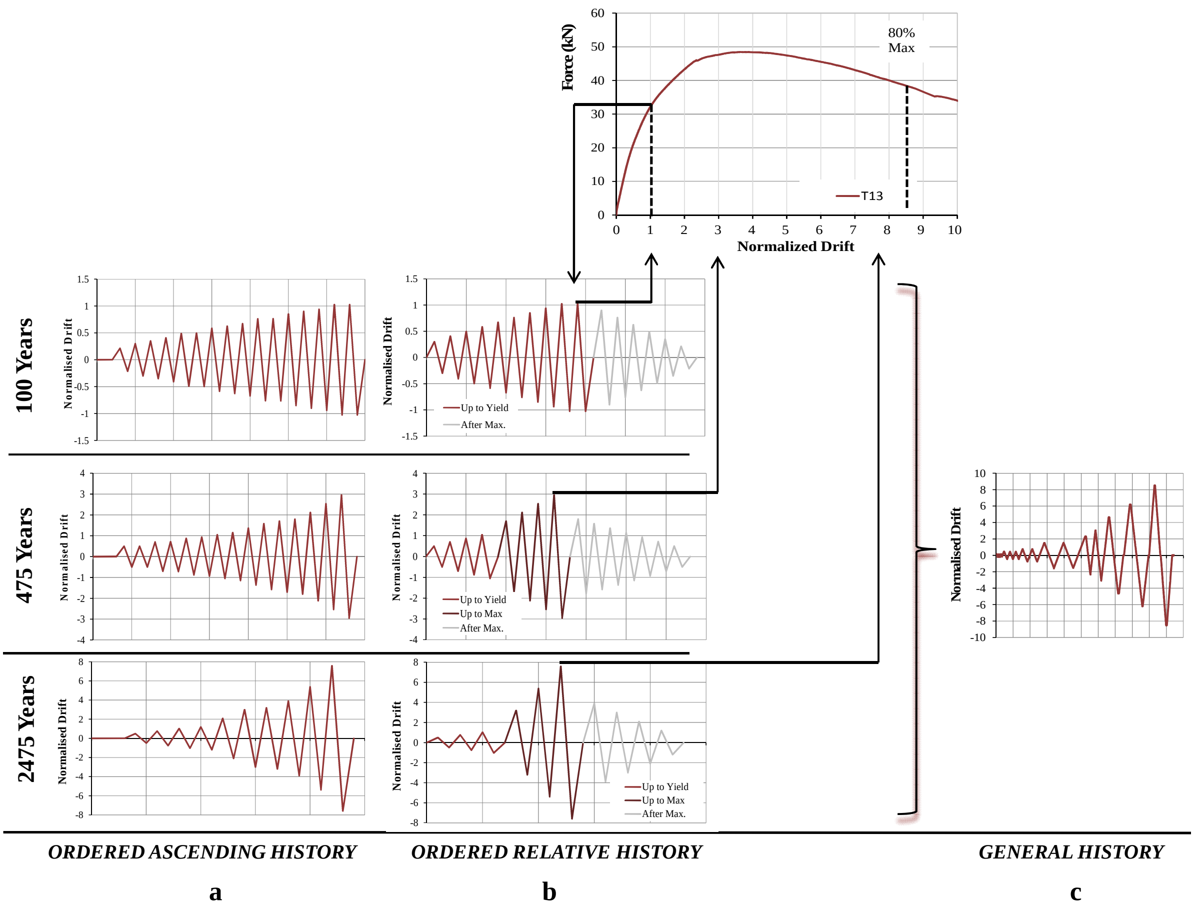

Figure 5. Derived load history patterns.

In the second set (Figure 5b), the demand histories are divided into 3 sections. The first section constitutes all the cycles up to yield, the second section constitutes all the cycles between yield and the maximum excursion, and the third section constitutes all the cycles between the maximum and the final position at the end of the analysis. The first 2 sections are arranged in ascending order, while the latter section is arranged in descending order. The relevance of the third section may not be necessarily important if there is a large difference between the size of the maximum cycle and subsequent cycles. This set of loading histories would be expected to describe adequately the cumulative damage aspect of test specimens since it incorporates the full number of cycles, the relative amplitudes and the sequence of excursions of important segments of the response history.

A single time history representing the 3 performance levels is required since the number of available samples is limited. A general loading history is therefore computed and consists of parts of the three ordered relative histories. The first section of this load history is composed of the first part of the ordered relative history for 100 years return period. The second part of the general history consists of a combination of the second part of the ordered relative histories associated with the 475 and the 2475 year return periods. The general history was adopted for the testing campaign in Borg et al. (2012). The form of the loading history presented may be valid for the case considered here, and may not be adequate to be used for other components in other circumstances.

3. CYCLIC TESTS ON R.C. ELEMENTS USING DIFFERENT HISTORY PATTERNS

3.1. Experimental Campaign

3.1.1 Test set-up

The experiments were carried out in the structural lab of the Civil Engineering Department at the University of Aveiro. The RC column model consists of a cantilever representing half the depth of a storey (Figure 3). The setup is in the horizontal plane (Figure 6), where the foundation is fixed by two metallic frames, and the lateral load is applied at the top of the cantilever by a hydraulic actuator in displacement controlled mode. The gravity load is applied parallel to the axis of the element and on the tip of the column by a static hydraulic actuator. The axial load system is hyper static and excludes P-Delta effects.

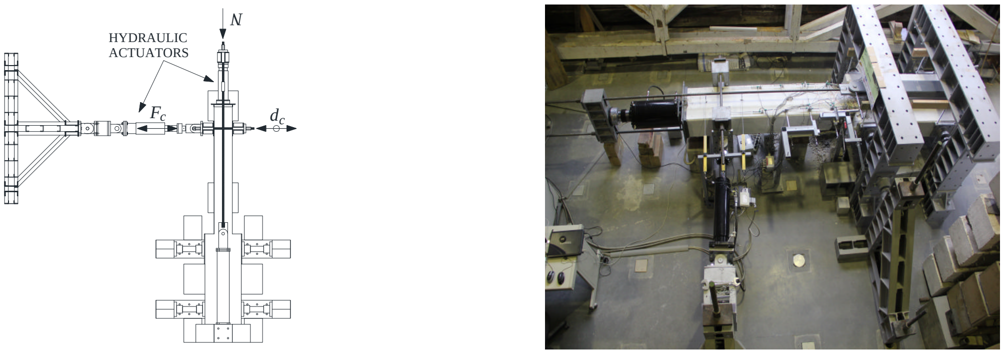

Figure 6. Test setup for column specimens.

3.1.2. Experimental campaign and loading histories

Two types of cross sections were considered in the testing campaign (Figure 7), in total having 6 specimens. Three square cross section specimens were tested with incremental loading histories (Figure 8) having different number of cycles at each drift level. For T14 the load history derived in Section 2 was used. Test T1b was based on the load history suggested by Krawlinker (1996), and T1a was an improvised loading history where, the same drift amplitude was applied until no considerable strength decay was further observed. T13 was the monotonic test. The rectangular section T5 was also loaded with the history obtained in Section 2. The history of the corresponding specimen T4, consisted in a slightly larger number of cycles, with cycles alternating in amplitude size for cycles close to the maximum deformation. In order to obtain the same loading ratio the axial load of the square section was taken as 450kN, while that for the rectangular section was taken as 750kN.

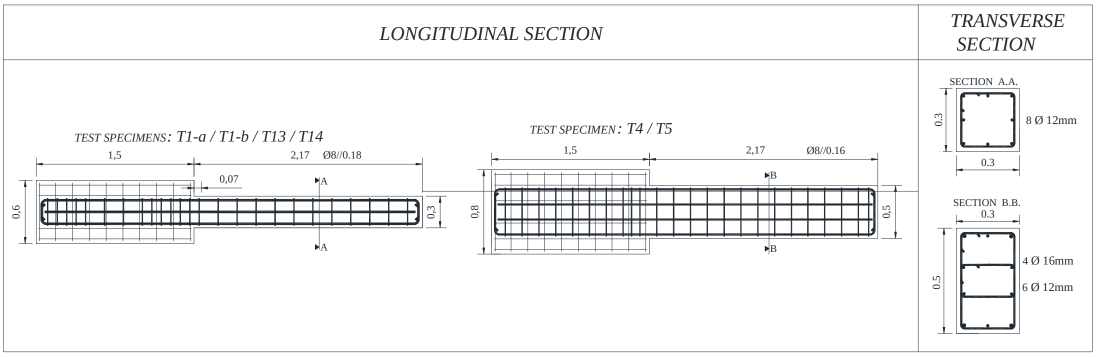

Figure 7. Longitudinal and transverse sections showing the detailing and geometry of the column specimens.

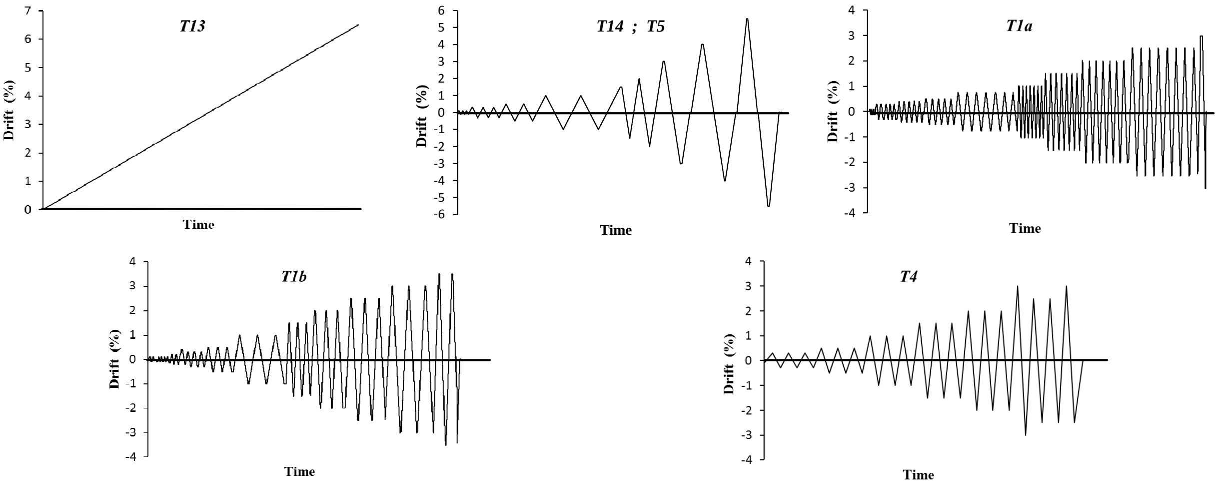

Figure 8. Loading histories for the experimental campaign.

3.2. Results of the Experimental Campaign Comparing Cyclic Loading Patterns

Figure 9 shows the force-drift preliminary results of the tested specimens. Figure 9a shows the envelope of the response of each of the 4 square columns. It indicates that the number of cycles prior to ultimate have an influence on the occurrence of this limit state. The larger the number of intermediate cycles, the larger is the strength decay. Hence, the ultimate value occurs at a lower value of deformation. It is also observed that the monotonic curve follows the same envelope up to and slightly beyond yielding. As a result, in the computation of the loading history, assuming the normalisation about the yield of the demand histories obtained from the analysis is reasonable. The ultimate limit state part of the monotonic curve, is quite distinct from the cyclic curves. Therefore normalising the response history about this point would have resulted in an unrealistic loading regime. These indicative results also confirm the trend of the experimental results (Figure 1) by Takemura et al., (1997). Failure occurs at a lower value of drift, when a larger number of loading cycles is employed, particularly after yielding occurs.

Figure 9b shows that T4 fails at 2.5% drift. This occurs a number of cycles after the maximum value is reached. This indicates that the subsequent cycles of significant amplitude, that occur after the maximum value, may be critical and have considerable effects on the performance of a structural element. This shows the importance and relevance of the ordered relevant histories (Figure 5) and the inclusion of cycles beyond the maximum with a significant amplitude.

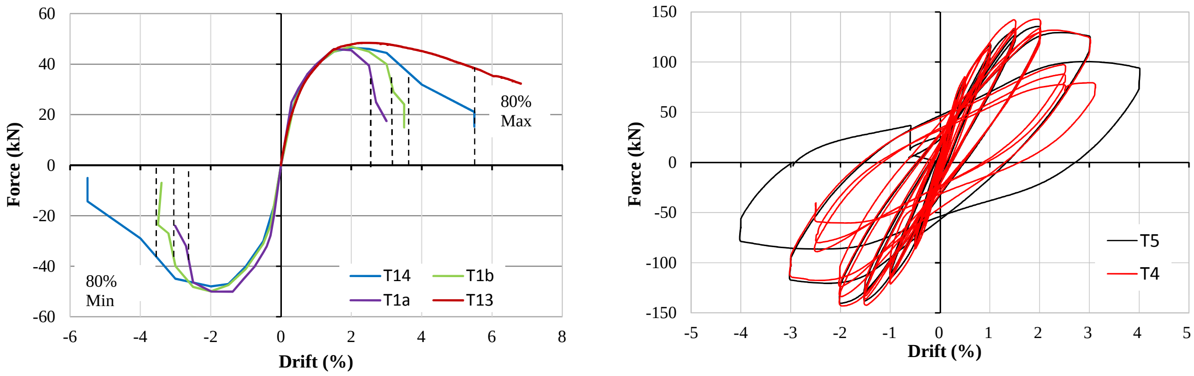

Figure 9. Comparison of the capacity of the column specimens: (a) Force-drift envelopes for the square section specimens, (b) Force drift hysteresis for the rectangular elements specimens.

4. CONCLUSIONS AND FURTHER WORK

A case study for the development of a loading history for a low-cycle fatigue testing campaign is presented. The process involves direct reference to earthquake loading associated with different damage criteria. The proposed loading histories represent realistically the total number of relevant cycles, the relative amplitudes and sequence of excursions. As a result, the cumulative damage response can be appropriately represented at that particular performance level.

Preliminary results of low cycle fatigue tests show the importance of the number of loading cycles and the loading pattern on the behaviour of RC elements. For the assessment of RC elements, if load cycle fatigue tests are used, it is important to have a loading history that realistically simulates a response that the element might undergo in case of an earthquake.

Every excursion in the inelastic range affects the stiffness, strength and deformation. The data describing the behaviour of the tested specimens is also being interpreted and investigated further in order to quantify the effects of different loading histories on energy dissipation, type of damage development, damping, strength degradation and stiffness degradation. This will help in understanding of effects a loading regime has on damage quantification particularly at moderate levels of damage.

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