Towards displacement-based seismic assessment in Europe

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ABSTRACT: As part of an on-going national research project in Italy called the RELUIS project, various developments are being made on the front of displacement-based assessment (DBA). This paper provides a review of the DBA approach and highlights recent developments that have been made to general aspects of the methodology, describing new proposals for the identification of the probability of exceeding key limit states. Research findings and outstanding challenges are then reviewed for different structural typologies, including reinforced concrete, masonry, timber, and steel buildings. The paper demonstrates that significant developments have been made for a wide range of structural typologies. However, it is also concluded that further research is required to find more simplified but sufficiently accurate means of considering the wide range of failure mechanisms that can develop in European buildings.

1 INTRODUCTION

1.1 Motivations for displacement-based assessment methods

Traditional seismic assessment methods have tended to be force-based, relying on a simple comparison of estimated base shear capacity and base shear demand specified by a code. As pointed out by Priestley et al. (2007), the problems with this approach are that: (i) No assessment is made of the actual displacement or ductility capacity, (ii) No capacity design check is included to determine undesirable failure modes, and (iii) no estimate is made of the risk of a structure which is deemed to fail the strength check. Recognising such limitations, a number of different displacement-based design (DBD) and assessment procedures have been proposed and for design, the Direct DBD approach is one of the most developed with a text (Priestley et al. 2007) and a Model Code (Sullivan et al. 2012) on the subject. A general means of undertaking displacement-based seismic assessment (DBA) was proposed in the nineties (Priestley, 1997) and is also included in Priestley et al. (2007). However, the general DBA approach (which will shortly be reviewed in Section 2) has not undergone significant developments since these initial proposals and thus, the subject of DBA is currently a research line in an Italian National Research project known as the RELUIS project.

1.2 The RELUIS project

The 2010-2013 RELUIS project (www.reluis.it) refers to a research initiative of the Laboratories University Network of seismic engineering (ReLUIS), founded in 2003, as an inter-university consortium with the purpose of coordinating and funding University Laboratories in Italy that are active in the field of seismic engineering. The 2010-2013 RELUIS project includes three main research lines: (i) development of a platform for the assessment and management of seismic risk of existing buildings, (ii) revision and improvement of national standards for earthquake engineering, and (iii) development of new tools and technologies for monitoring, managing and reducing seismic risk. The development of the DBA approach falls within the activities of research line 1, and includes the nine research areas and universities listed in Table 1.

Table 1. Displacement-Based Assessment Research Group for the RELUIS project.

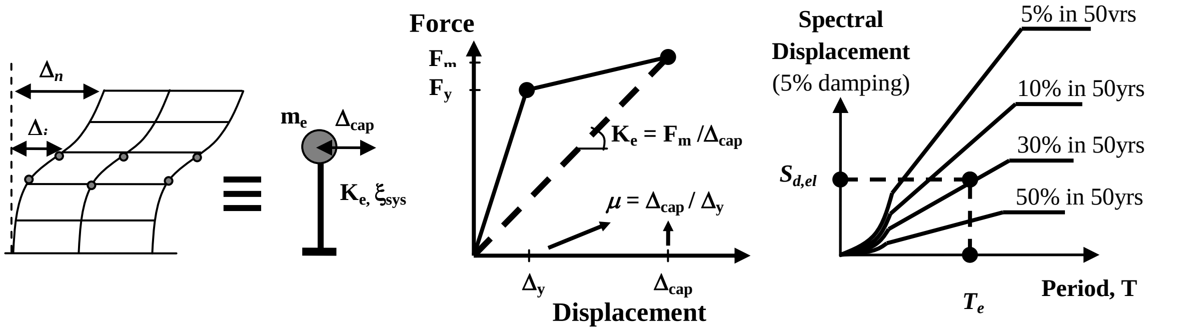
Research Area	Responsible University	Research Leader
1. General DBA aspects	Pavia	Calvi & Sullivan
2. RC Buildings	Bologna and Pavia	Benedetti and Sullivan
3. Pre-Cast RC Buildings	Bergamo	Riva
4. Masonry Buildings	Genova and Pavia	Lagomarsino and Magenes
5. Steel and Composite Structures	Naples Federico II & Pisa	Della Corte and Salvatore
6. Timber Structures	Trento	Zanon & Piazza
7. Bridges	Basilicata & Poly. of Milan	Cardone and Petrini
8. Retaining Structures	Perugia	Pane
9. Foundations & SSI	Polytechnic of Milan	Paolucci

The aim of this paper is to highlight recent developments that have been made to general aspects of the DBA methodology, and briefly review research findings and outstanding challenges for different structural typologies, including reinforced concrete, masonry, timber, and steel buildings.

2 OVERVIEW OF THE DIRECT DISPLACEMENT-BASED ASSESSMENT APPROACH

2.1 Identification of the expected force-displacement capacity

The first task in the DBA approach is to evaluate the likely force-displacement response up until the point that a limit state is reached. The limit state of interest will depend on the purposes of the assessment but, as is argued by Priestley et al. (2007), the collapse-prevention limit state will typically be the key limit state for existing structures. Assessment of the likely force-displacement response up to the collapse-prevention limit state requires identification of the likely inelastic mechanism and this can be achieved either through pushover analyses or a hand calculation procedure such as that explained in Priestley et al. (2007). For example, in the case of a RC frame structure either a column-sway or a beam sway mechanism might develop, and in the event that a column-sway mechanism is expected, the designer should identify at which floor it is expected to occur. It will be evident that for existing structures numerous failure mechanisms could be possible and may not be easily identifiable, particularly for structures built prior to the introduction of seismic design codes. Thus, some consideration of uncertainty in the assessment should be made and this is discussed further in Section 3. As shown in Figure 1b, key characteristics of the assessed force-displacement response are the displacement capacity, Δ_{cap}, and corresponding force, F_m, as well as the yield displacement, Δ_y, which can be used to estimate the system ductility capacity as $\mu=\Delta_{cap}/\Delta_y$.



(a) Equivalent SDOF representation of structure at critical limit state **(b) Force-Displacement (pushover) curve for equivalent SDOF system** **(c) Identification of seismic intensity expected to create limit state damage**

Figure 1. Overview of displacement-based assessment approach (after Priestley et al. 2007).

The assessed force-displacement response shown in Figure 1b should be that associated with a single-degree-of-freedom (SDOF) representation of the structure, as illustrated in Figure 1a. For multi-degree-of-freedom (MDOF) structures the limit state storey displacements, Δ_i, and the storey masses, m_i, can be inserted into the Equation 1 to identify the substitute structure characteristic displacement capacity, Δ_{cap}.

$$\Delta_{cap} = \frac{\sum m_i \Delta_i^2}{\sum m_i \Delta_i} \tag{1}$$

The system displacement capacity can be divided into the total equivalent lateral force (effective 1st mode base shear), F_m, to give the effective stiffness, $K_e = F_m/\Delta_{cap}$, which is subsequently used to evaluate the seismic intensity that would cause the limit state to be exceeded, as explained next.

2.2 Comparing seismic demands with structural capacity

Traditional seismic assessment methods tend to adopt a pass/fail assessment approach in which the capacity of the structure is deemed to either satisfy, or not, a prescribed code intensity level. In DBA, Priestley et al. (2007) argue that a more rational assessment of the seismic risk of a structure can be made not through a pass/fail approach but rather by evaluating the likelihood with which the limit state capacity will be exceeded. Priestley et al. (2007) suggest that this can be done using a DBA approach as shown in Figure 1c, in which the equivalent elastic spectral displacement capacity of the building, $S_{d,el}$, is paired with the effective period, T_e, and is compared with spectral displacement demands for different return period earthquake events (indicated in Figure 1c as the probability of occurrence in 50years). For the example illustrated in Figure 1c, the assessment would suggest that the probability of exceeding the limit state capacity is 30% in a 50year period.

In Italy seismic hazard data is provided for nine different intensity levels, with response spectra provided for 30 year return period events (with 81% probability in 50years) through to 2475 year return period events (2% probability in 50years). As such, a good range of displacement spectra are available to permit the operation shown in Figure 1c. Consequently, to undertake a displacement-based an assessment using the force-displacement curve presented in Figure 1b, one must first identify the effective period, T_e, as:

$$T_e = 2\pi \sqrt{\frac{m_e}{K_e}} \tag{2}$$

where m_e is the effective mass given by:

$$m_e = \frac{\left(\sum m_i \Delta_i\right)^2}{\sum m_i \Delta_i^2} \tag{3}$$

The elastic spectral displacement capacity of the building, $S_{d,el}$, should then be obtained from the displacement capacity, Δ_{cap}, as:

$$S_{d,el} = \frac{\Delta_{cap}}{\eta} \tag{4}$$

where η is an empirical ductility-dependent modification factor that depends on the hysteretic properties of the structure. The data presented in Priestley et al. (2007) leads to the following spectral displacement modification factor for RC structures (not subject to near-field earthquakes) that depends only on the displacement ductility demand, μ (as per Figure 1b):

$$\eta = \sqrt{\frac{0.07}{0.07 + 0.444\left(\frac{\mu - 1}{\mu\pi}\right)}} \quad (5)$$

As such, the procedure is relatively simple in concept. The main challenge lies in identification of the correct force-displacement response which is likely to be fraught with uncertainty (but note that this difficulty is not assessment method-dependent). In addition, one should have access to suitable expressions for the spectral displacement modification factor, such as that given in Equation 5. Both these aspects have been included in the general research activities of the current RELUIS project and the next section will explain some of the advancements made in order to deal with uncertainties.

3 DEVELOPING THE PROBABILISTIC BASIS OF THE APPROACH

3.1 Accounting for uncertainties

There are many uncertainties in any seismic assessment. One of the greatest sources of uncertainty lies in the ground motion intensity but for existing buildings the structural characterisation may also be very uncertain. In probabilistic assessments, uncertainties tend to be classified as either aleatoric or epistemic and there are several different proposed means of dealing with them. Interested readers could refer to works such as Bradley and Dhakal (2008) or fib Bulletin 68 (fib, 2012) for a critical discussion of probabilistic methods. Reviewing the procedure proposed by Priestley et al.(2007), it is apparent that the effects of uncertainty are not accounted for in identifying a probability of exceedence from Figure 1c. During the RELUIS project it has been proposed that a simple means of accounting for uncertainty in both the demand and the capacity in DBA, is to use the SAC-FEMA approach of Cornell et al. (2002) simplified in line with the recommendations of Fajfar and Dolsek (2010). Subsequently, the probability of the exceedence of a given limit state $P_{LS,x}$ with a 50% confidence level can be estimated as:

$$P_{LS,x} = \tilde{H}\left(S_{a,\tilde{C}}\right)C_f \quad (6)$$

where $\tilde{H}$ ($S_{a,C}$) is the median value of the hazard function at the seismic intensity $S_{a,C}$, which causes a selected limit state to develop, and this is essentially the probability value that is being identified in the Priestley et al. (2007) DBA approach shown in Figure 1c. The factor C_f accounts for the dispersion (uncertainty) in demand and capacity and, assuming log-normal distributions of demand and capacity, Cornell et al. (2002) report that it can be computed as:

$$C_f = \exp\left[\frac{k^2}{2b^2}\left(\beta_{DR}^2 + \beta_{CR}^2\right)\right] \quad (7)$$

where k is a constant (with values of around 2.0 or 3.0 typical in Italy) used in a power expression to relate the hazard with a probability of exceedence, b is a constant that relates the EDP to the intensity measure and is typically taken as 1.0, and β_{DR} and β_{CR} are dispersion measures for randomness in demand and capacity respectively. Fajfar and Dolsek (2010) report that reliable data on dispersion is not yet available and they used a value of (β_{DR}^2 + β_{CR}^2) = 0.2025. The more recent ATC-58 (2011) document provides many different values of dispersion to account or different phenomena.

Using k=2.0, b=1.0 and the dispersion values of Fajfar and Dolsek, one finds from Eq.(5) that the estimated probability of exceeding the key limit state is 1.5 times that estimated without account for uncertainty. This gives an indication of the effect that accounting for uncertainty can have on the assessed probability and note that, formulated in this way, it always leads to an increase in the likelihood of exceeding a given limit state. The accuracy of the SAC-FEMA approach is limited (see Aslani and Miranda 2005, Bradley and Dhakal 2008) but it does permit consideration of uncertainty and therefore its implementation within the DBA procedure is considered to be a useful development.

4 RESEARCH INTO THE ASSESSMENT OF RC STRUCTURES

4.1 RC Frames with Masonry Infill

A common construction solution in Italy involves the use of masonry-infilled RC frames. This is despite the fact that many previous earthquakes, including the 2008 L'Aquila earthquake as shown in Figure 2, have highlighted the vulnerability and poor performance of masonry infills. In order to improve the tools available for the assessment of RC frames with masonry infill, the University of Bologna has been undertaking numerical investigations to consider how the peak displacement demands on such structures can be estimated. They are investigating different options, including whether or not the stiffness of the masonry infill requires explicit evaluation or whether a general modification factor can be used to modify the response of a structural model that considers only the bare RC frame. In parallel to this, the University of Pavia has been investigating drift limits that could be suitable for different damage limit states of RC frames with masonry infill. Hak et al. (2012) provide expressions for the drift capacity as a function of the masonry infill properties and the panel dimensions. Drift limits can be in the order of 0.3% for the damage limitation state, suggesting (as is seen in reality) that masonry infills can be heavily damaged before RC frames even yield, as illustrated on the right-side of Figure 2.

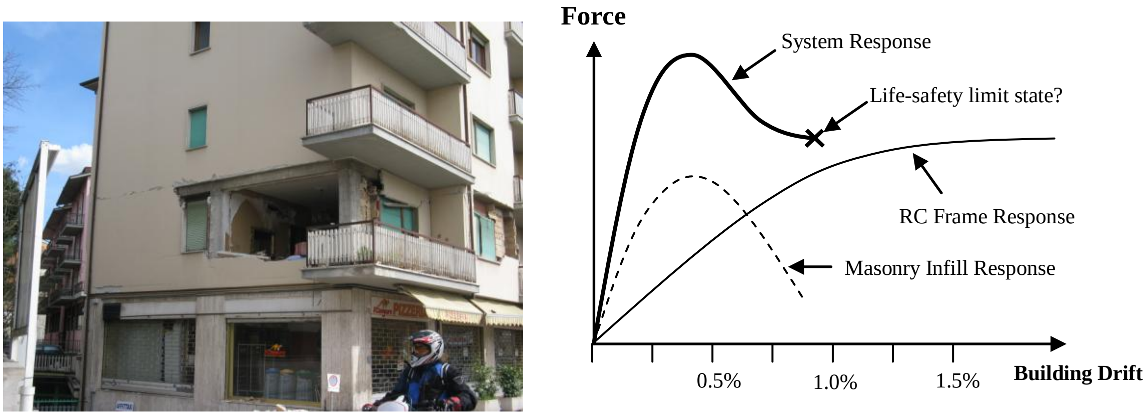
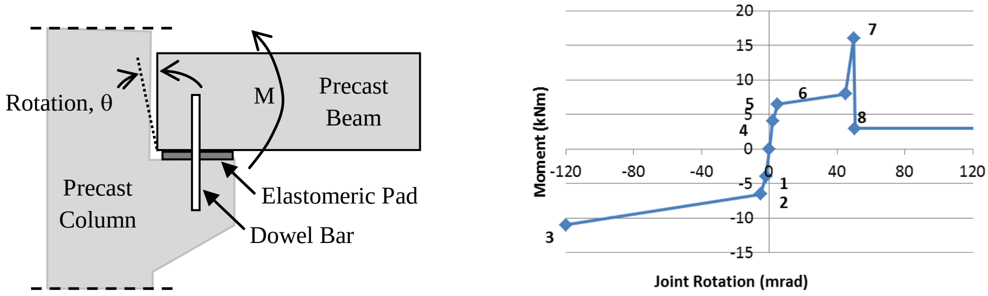


Figure 2. Photo (left) of damage to a RC frame building with masonry infill following the 2009 L'Aquila earthquake and idealised force-displacement response (right).

Another research activity undertaken by the University of Pavia in relation to the assessment of RC structures with masonry infill has examined a 6-storey RC frame building with two different infill configurations: the first with full masonry infill and the second with an open ground storey with full masonry infill above the first floor. Results of incremental dynamic analyses indicate that structures with uniform infill are less likely to collapse. However, the responses in isolated floors above the first floor are considerably improved for soft storey cases, provided that the large displacement demands at the soft storey are sustained. This in turn has suggested that the need, and best technique, for retrofit of these structures will depend on the seismic hazard and acceptable risk, and that likely financial losses should be considered in such an assessment.

4.2 Pre-cast RC Frames

The 2012 Emilia-Romagna earthquake highlighted the vulnerability of pre-cast RC frame structures in Italy. As part of the RELUIS project, the University of Bergamo has been developing tools for the displacement-based assessment of precast frames. In particular, given that careful consideration of precast connections is fundamental for the overall assessment of precast structures, the behaviour and the failure mode of common beam-column connections have been investigated and simplified procedures for the definition of force-displacement curves have been proposed. Figure 3a plots the moment-rotation relationship (right) for a pre-cast Beam-Column connection (left) realised with an elastomeric pad and a steel dowel bar. The derived moment-rotation relationship is different for clockwise or counter-clockwise moments, due to the possible eccentricity of the dowel bars and the possible contact between the top of the beam and the column (branch 6 to 7 in the curve shown). This joint model can be utilised within a global model of a pre-cast frame to establish the displacement capacity and resistance for subsequent application of the DBA procedure described in section 2.



(a) (b)

Figure 3. (a) Sketch of beam-column connection common in industrial pre-cast buildings in Italy and (b) typical moment-rotation behaviour of such connections.

5 RESEARCH INTO THE ASSESSMENT OF MASONRY STRUCTURES

5.1 Multi-level assessment strategy

As part of the University of Genova's research activities into unreinforced masonry structures, the definition of performance limit states on the force-displacement capacity curve is made through a multi-criteria approach, which considers three different scales in the building:

- the element scale (damage in single piers and spandrel beams);
- the macroelement scale (mechanism in each wall of the building);
- the global scale (reaching of the maximum strength and progressive global reduction for increasing displacements).

The motivation for this approach is related to the way that masonry structures can respond either as an assemblage of individual structures or as a single global structure. For example, considering the macroelement scale (wall), it is important to consider the role of the stiffness of floors, which can share the horizontal seismic actions among walls. If floors are flexible, once a limit state is reached at the macroelement scale, the same limit state can be assumed to be reached at a global scale; on the contrary, the progression of damage in a wall should be limited by the other walls in the case that a very stiff diaphragm is present to redistribute loads and limit deformations.

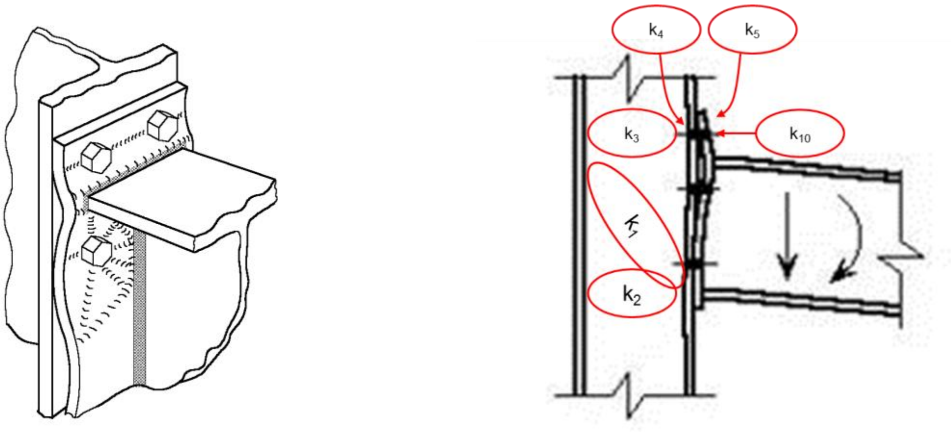
5.2 Displacement demands on Masonry Structures

As part of the University of Pavia's research activities related to masonry structures, efforts are being made to obtain improved estimates of displacement demands on masonry structures. It is recognised that masonry structures can exhibit various types of failure mechanisms, with in-plane failures of walls being dominated either by shear or flexural behaviour, and that the energy dissipated by each mechanism is likely to be significantly different. Consequently, work is progressing to develop simplified expressions for the spectral displacement modification factor (Eq.5) as a function of the type of failure mechanism expected.

6 ASSESSMENT OF STEEL, COMPOSITE AND TIMBER STRUCTURES

6.1 Assessment of joints in Steel and Composite Structures

An important focus of the research being undertaken by the University of Naples, Federico II, for steel structures and the University of Pisa for composite structures, is the examination of joint behaviour and capacity. In recent years the Eurocodes have seen the implementation of what is known as a component-method for the evaluation of the strength and stiffness of steel and composite joints. The procedure sees the evaluation of individual strength or stiffness components (see Fig. 4b) associated with the complete loadpath through a joint, which are then combined to establish the overall joint strength or stiffness. In the assessment of existing structures in practice, the application of the Eurocode procedure is not particularly simple and through application to real case-study structures, efforts are being made to provide and test guidelines for the implementation of the component approach.



(a) (b)

Figure 4. (a) Sketch of local deformations within a steel beam-column joint and (b) an example of various stiffness components that would be considered in evaluating the total joint stiffness.

6.2 Assessment of Timber Structures

As part of the RELUIS project, the University of Trento has developed an analytical model to evaluate the ultimate displacement and estimate the matching equivalent viscous damping, as a function of the mechanical properties and geometry, for timber framed wall structures. The proposed model is based on the direct relationship between the building displacement profile and the deformed shape of construction elements, with consideration of the likely mechanism. Expressions for displacement and equivalent viscous damping at the ultimate limit state are being validated numerically and experimentally; these experiments include monotonic and cyclic tests on a set of structural elements, according to the European standards.

7 NEED FOR ADDITIONAL RESEARCH

The success of the DBA procedure would appear to rely on the correct identification of the failure mechanism, as this will influence the anticipated force-displacement response and displacement capacity. However, the identification of the correct mechanism, either by hand calculations or a non-linear model is not a simple task, owing to the many possibilities that could eventuate and a general lack of proven expressions for the strength and deformability of certain mechanisms. Consider, for example, an infilled RC frame where aside from the consideration of beam versus column flexural hinging and various types of masonry mechanisms, one should also assess the possibility of joint failures, shear failures of beams or columns, confinement problems, lap-splice problems, longitudinal bar slip, foundation mechanisms and floor diaphragm capacity. In assessing such phenomena, one should keep an eye on complex effects such as torsion, p-delta and uncertain vertical actions.

Given these complexities, it is suggested that the engineering profession would greatly benefit from a simplified approach in which the engineer could choose a select number of possible mechanisms to evaluate. The assessment procedure could then penalise assessments that only consider a limited number of mechanisms by increasing the uncertainty (see Eq.7) when estimating the likely probability of exceedence. However, any simplifications to the approach would need to be limited to ensure that engineers do not lose sight of the real factors affecting the seismic response of buildings in earthquakes. With this in mind, the best means of making simplifications will require future research.

8 CONCLUSIONS

The RELUIS project has permitted several developments to be made on the front of displacement-based assessment (DBA). A general development includes the allowance for uncertainty when estimating the probability of exceeding a certain limit state. Research activities for specific building typologies include new procedures for the estimation of peak displacement demands on infill RC frame structures and masonry structures, guidelines for application of the component method to steel and composite joints and new displacement estimates for timber framed wall structures. Published findings from the project are still in preparation and interested readers should refer to the RELUIS website (www.reluis.it) where a list of final publications will be provided in due course. In this paper, it is concluded that even though significant developments have been made for a wide range of structural typologies, further research is required to find more simplified but sufficiently accurate means of considering the wide range of failure mechanisms that can develop in European buildings.

9 ACKNOWLEDGEMENT

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