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DEVELOPMENT OF NONLINEAR ANALYSIS MODELS FOR SHEAR WALL REINFORCED-CONCRETE STRUCTURES USING THE FINITE-ELEMENT METHOD

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Abstract: Although significant progress in the modelling of the nonlinear response of reinforced-concrete (RC) structures at the element level has been achieved in the past decades, reliable and accurate analysis models at the system level for RC structures are scarce. Due to the complexity of elements required to model the 3D response of RC panels, nonlinear analysis of complete RC structures is avoided and instead the response of selected sub-assemblies, isolated from the rest of the structure, is examined in usual design practice. As a result, there is substantial uncertainty on the response of complete RC buildings, making it impossible to analyze global failure modes and making the design more complicated and potentially unsafe. Although simple structures can be designed and analyzed based on the response of their components with good accuracy, RC shear wall buildings with complex geometries or under extreme loading necessitate the analysis of the full structure. Recent progress in the development of efficient element formulations to simulate the nonlinear in-plane and out-of-plane response of RC panels, and the availability of experimental data on the response of full shear wall structures, offers the possibility of developing reliable and efficient analysis models for entire RC structures under static and dynamic loads. This research discusses techniques to address the challenges found in the analysis of full, 3D RC shear wall structures such as the transmission of forces between beam and column elements and walls, the modelling of shear wall elements with confined boundary elements or flanges, and the performance of fiber-section elements vs. multilayered shell elements.

1 INTRODUCTION

In recent years, shear walls have caused the height of RC buildings to increase significantly, making their structural behavior more complicated. This global behavior cannot be predicted by modelling the building elements and putting them together, the need of a tool that can describe the behavior of a complex RC structure is needed. Most of the research in RC favours the study of the effects of dynamic loads at the element level, generating FEA models for shear resisting elements.

Mansour et al. developed a cyclic stress-strain curve and compared it with the results from six cyclic tests of RC panels. These tests showed accurate results, but the complexity of the material model deems it hard to implement when analyzing a complete RC structure. (Mansour et al. 2001).

Zhong used Cyclic Softened Membrane Model for reinforced concrete, to simulate the response of panels, shear walls and bridge piers. This model transforms the biaxial strains into uniaxial strains and then analyzes the element with uniaxial material models. Again, the computational power needed to perform these calculations is considerable, and a bidimensional material model could be used to simplify analysis for complex structures. (Zhong 2005)

Legeron et al. chose to approach the behavior of reinforced concrete employing damage mechanics, more specifically a 2D concrete damage material model that can accurately represent concrete behavior in all its stages. They compared their results with tests of beams, columns and bridge piers. (Legeron et al. 2005)

Mi-Geum used total strain based models to describe reinforced concrete behavior. The model was implemented in FEA software, and compared with the results of RC shear walls tests. Total strain based models describe the behavior of concrete in two dimensions if they are combined with shear friction modelling, this creates more complex models that require more computational power than damage models. (Mi-Geum 2008).

Other approaches choose to approximate the behavior of shear resisting elements, by decoupling the shear resistance from the moment resistance, some by using different sub-elements to create a complex macro-element (Kolozvari et al. 2017), and others by creating lattice or truss elements that describe the behavior of a shear wall (Mazars et al. 2002, Mazars et al. 2015).

Tall buildings have many conflicting requirements and complex element interactions that separate analyses cannot integrate. The impact of wind and seismic forces is an important aspect of the design and later behavior of the structure, thus the need of a model strategy to describe this complex behavior without losing the ability of observing the element performance, as well as the performance of the structure as a whole. The dynamic response needs to be described accurately using the most time-effective method when developing the model.

In this paper, a complete approach to the prediction of full RC shear wall structures subjected to dynamic loadings is presented. Some guidance is provided on which modelling techniques to follow when dealing with this type of structures, such as the modelling of shear wall elements and the performance of fiber-section elements vs. multilayered shell elements. The software was used to predict the behavior of simple RC structural components tested under monotonic and dynamic loading. The advantages and shortcomings of each modelling technique are discussed in terms of strength, deformation and failure modes. It was shown that the global response of these tests was predicted quite well, so finally the response of a 3D, shear wall building is simulated using the approach proposed. This approach is a powerful tool for seismic analysis of complex RC structures in which the superposition of the behavior of the sub-elements is not enough to accurately predict the response of the structure.

1.1 Objectives

1. Determine when is best to use uniaxial elements and bidimensional elements in FEA software when modelling reinforced concrete structures.
2. Combine different types of FEA elements, analysis methods and modelling techniques to exploit their strengths and outweigh their weaknesses.
3. Find the material models that resemble the actual behavior of steel and concrete, when used in reinforced concrete structures.
4. Develop a model that describe the real behavior of complex structures under seismic loading, minimizing analysis time and computational power.

2 MODEL STRATEGIES

The Open System for Earthquake Engineering Simulation (OpenSees) is a Finite Element Analysis software for simulating the seismic response of different systems (Mazzoni 2017). Developed by the Pacific Earthquake Engineering Research Center, and has different material types, uniaxial and bidimensional elements, and a wide range of algorithms and solution methods. It is an open-source software that allows users to modify the source code and add new elements, materials and analysis types. In the OpenSees framework there are several materials and elements that can be implemented in any given model. One way to divide them is by the number of dimensions where their response can be measured; unidimensional, bidimensional, or tridimensional. In this research, the focus is in the first two types of elements and materials.

2.1 Modelling using unidimensional elements

To construct a section, the simplest elements that can be used are the unidimensional elements, also called fibers. These fibers contain an uniaxial material, an assigned cross-sectional area and a location within the section. The stresses that these fibers can carry are only normal stresses out of the plane of the section, but by assembling a fiber section, it can describe the behavior of an Euler-Bernoulli beam. The response that we can obtain from these elements are compression and tension behaviors as well as bending forces through the section.

When using a display recorder for the structure, these elements will be presented as a straight line and they will not display any visible change while analyzing, as observed in figure 1a)

2.2 Modelling using bidimensional elements

Bidimensional elements are called plate or shell elements, the behavior of a shell is given by the combined response of normal and shear stresses throughout the element in-plane with the section. Shells are linear quadrilateral elements, which can behave as either plane-strain or plane-stress; the out-of-plane behavior must be specified while creating the plate section, but their main components are the in-plane strains and stresses.

In the display recorder, as shown in figure 1b) all of the shell elements are shown, and also their relative stress distribution is represented by the change of the colors in each of the elements.

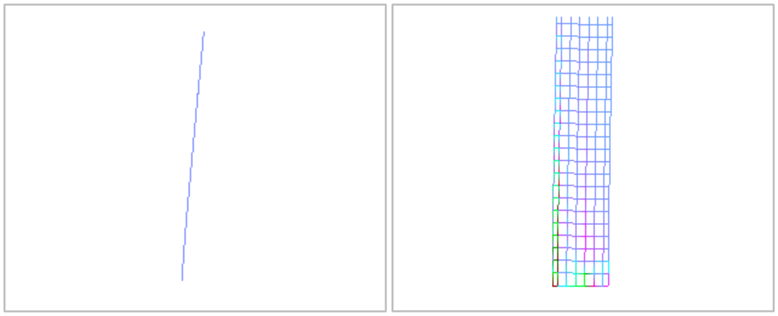


Figure 1: Beam element modelled with a) Fiber elements, and b) Shell elements

2.3 Fibers vs. Shells

Fiber elements are very simple to establish, but the results are not as accurate as the ones we obtain with shell elements. By analyzing only in one direction, the uniaxial elements lose the ability of describing what is happening in all the other axes; while shell elements consider also the effects of the shear forces within the element.

In elements where the main behavior of the cross section is regulated by normal stresses, using fiber elements is more efficient. An example of these elements are the Euler-Bernoulli beams, beams long enough to develop a linear distribution of the normal stresses in the section. In figure 2, it can be observed the difference of the results obtained when modelling beams with length-to-height ratio varying from 1 to 5, using fibers or shell elements.

The difference in the results is considerable when the beam has a ratio less than 2, and the results we obtain from the fiber elements are incorrect; this is a deep beam, where the shear response accounts for most of the stresses in the section. But as the ratio increases, the difference becomes negligible, proving that is safe to model this type of elements with fiber elements without losing any important accuracy in the results.

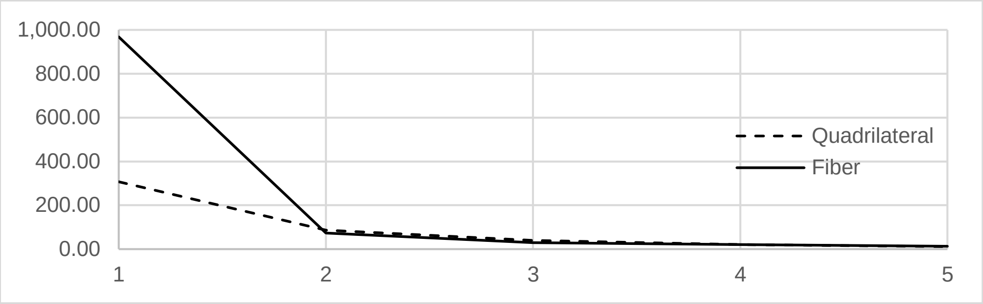


Figure 2: Cantilever beam resistance with fiber elements vs. shell elements

2.4 Combining fibers and shells

After analyzing the advantages and disadvantages of each type of element, adjustments can be made to any model to obtain the best results. The time consumed by the analysis, when using bidimensional elements is much larger than uniaxial elements, but the results obtained will be more accurate. Also, the form each element in a structure behaves impacts the definition of the type of elements to be used in the model. Knowing this compromises should be done between accuracy and time, depending on what is the final goal of the analysis, as well as the known behavior of the structural elements.

The way a structure behaves is important in the definition of their finite-element package counterparts, by knowing this a model can be simplified. To better explain this notion, in figure 3 is represented the behavior of a reinforced concrete deep I-beam 1m deep and 5m long, subjected to flexure. In this type of structures, the web will be dominated by shear stresses, while the flanges will be mostly subjected to normal stresses. The first model was developed using first a panel-fiber section, and then using fiber-section only.

For this type of elements is observed that neglecting the shear response of the element overestimates its stiffness. From these models it is observed that when an element is subjected principally to normal and bending forces and is slender enough, it is safe to use fibers to model it. But elements which resist important shear forces, the right path to follow is to create a model with shells. The correct combination of both will give an accurate and time-efficient model.

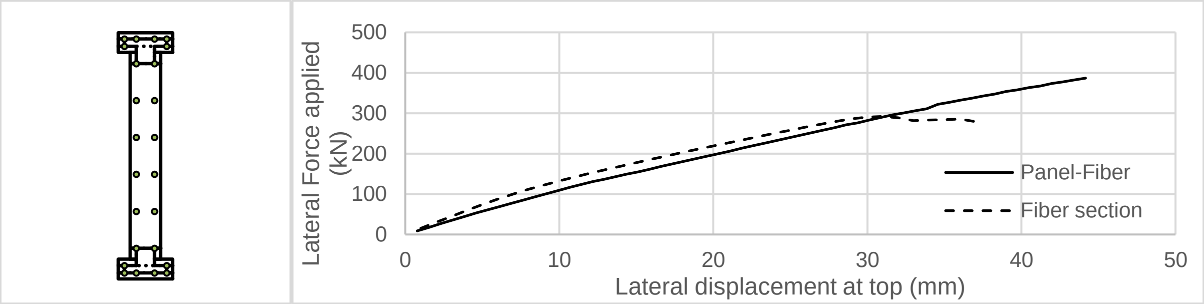


Figure 3: Force displacement of deep beam with different type of elements

The combination of different load-resisting systems provides a stiffer structure, as observed in figure 4. A frame is a very flexible structure, while a shear wall is much stiffer but very unstable by itself. When combining the both, a very stiff and stable structure is formed. The frame gives stability to the structure and the means to distribute the stresses throughout the shear wall.

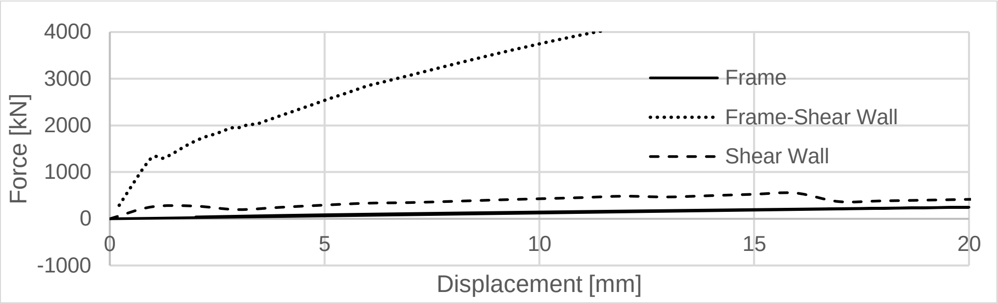


Figure 4: Force displacement of different structures

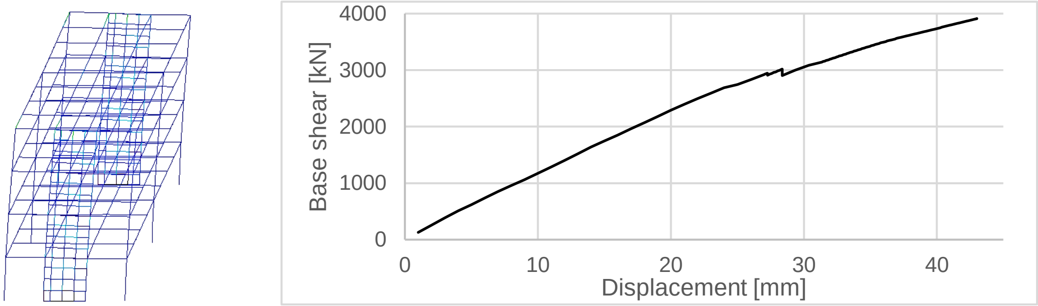
3 SEISMIC RESPONSE

3.1 Test and model description

A 4-storey reinforced concrete building with shear walls was constructed and subjected to the Kobe earthquake of 1995. The building was designed according to the Japanese seismic design code, and was tested in the E-defense shake table (Nagae et al. 2011). The structure consisted of a four-storey building with base dimensions of 14.4x7.2m, and height of 12m. Lateral support in the longitudinal or ‘z’ direction of the building, was provided by the frame system; in the transverse direction, lateral support was provided by reinforced concrete shear walls on each side of the building. The compressive strength of the concrete used in all the elements ranged from 30 to 41 MPa, the yielding stress of the reinforcement steel ranged from 370 to 450 MPa.

For this structure, actual material properties, dimensions, reinforcement and gravitational loads, were considered. Beams and columns were modelled using a Kent-Scott-Park concrete material (Scott, Park and Priestly 1982), a Giuffre-Menegotto-Pinto steel material with isotropic strain hardening (Menegotto and Pinto 1973), and fiber elements; considering confinement properties for the core concrete as explained by Mander (Mander, Priestly and Park 1988). Slabs and shear walls were modelled using a concrete Plane User Stress Material (Lu et al. 2015), the previous steel material, and shell elements. Bond-slip was also considered at the base of the columns. The model consists of 53 different sections, 462 nodes, 560 elements.

To have an approximation of the response of structure under lateral loading, pushover analyses were performed in both the ‘x’ and ‘z’ directions. As can be seen in figure 5, the expected response is according to the expected. In the pushover in ‘x’ direction, the behavior of the structure is governed by the stiffness of the shear walls, this provides a non-ductile quasi elastic behavior The response of the structure in the pushover in the ‘z’ direction is governed by the frame interaction, which gives a ductile response of the building, showing clearly a “yielding” point of the structure before failure.



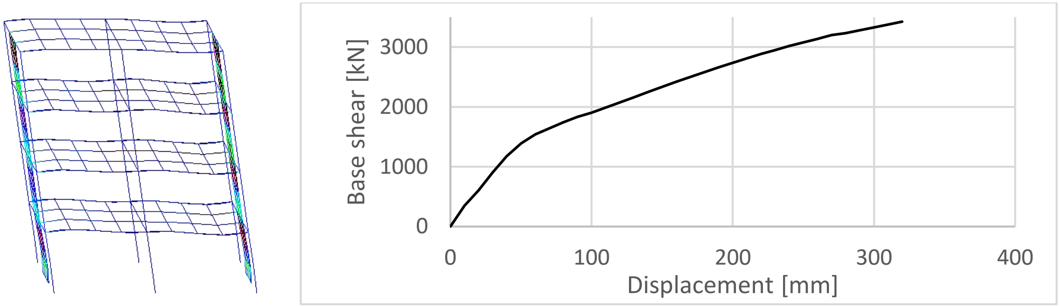


Figure 5: Base shear – top displacement of pushover analysis in a) ‘x’ direction, and b) ‘z’ direction

The test structure was subjected on the first day to the Kobe earthquake records at three different magnitudes 25%, 50% and 100%. On the second day, the structure was subjected to the Takatori earthquake records at 40% of its strength, followed by the 60% strength (Nagae et al. 2011). Test results are available only for the Kobe earthquake, which base accelerations are shown in figure 6, for its three directions.

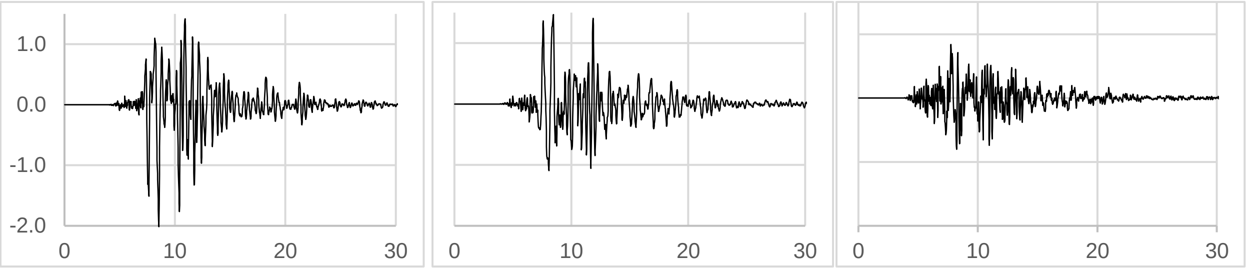


Figure 6: Kobe earthquake accelerations in the ‘x’, ‘z’ and vertical directions [g]

3.2 Results comparison

To illustrate the validity of the model, the results obtained from it are compared with the available test results. The base shear of the test was not measured, it was calculated using the acceleration inputs and multiplying them with the masses of the structure (Nagae et al. 2012). From the finite-element package model, the base shear was recorded as a sum of the reactions of each base node. Figure 7 a) and b), show the results for the Kobe 100% earthquake, from the FEA model and test respectively. From the graphs it is observed that the base shear of the structure approximates accurately the response of the test.

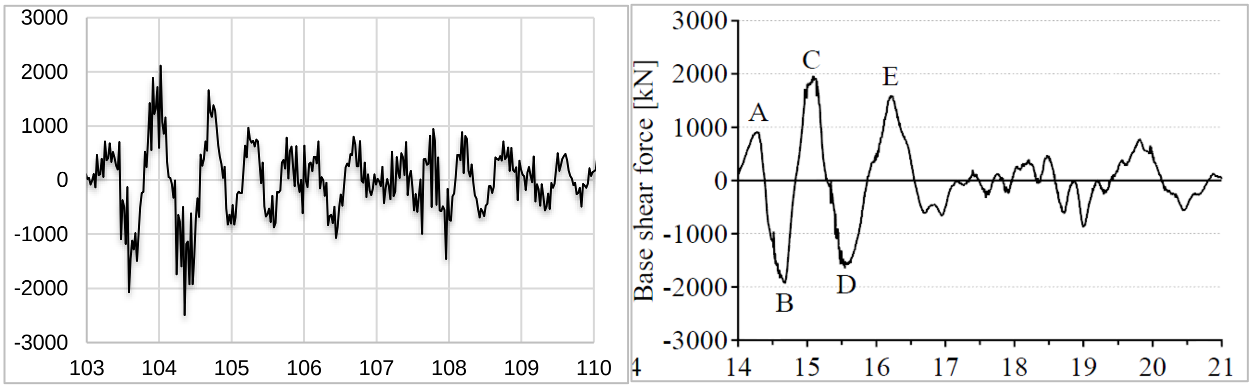


Figure 7: Base shear force with Kobe 100% earthquake from a) FEA model, and b) calculated (Nagae et al. 2012)

Then, the roof drift of the structure was measured. The peak roof drifts are available for the Kobe earthquake applied at 25%, 50% and 100%, these are 0.2% (23.5 mm), 0.84% (100.7 mm), and 2.54% (304.2 mm) for the 25%, 50% and 100% Kobe records respectively (Nagae et al. 2012). In figure 8, the results in both directions of the FEA model are plotted. The results show the peak roof drifts are 56.2, 101.2, and 291.3 mm for the 25%, 50% and 100% Kobe records respectively. The results from the model resemble closely what was measured during the test of the structure, showing that the model is accurate in representing the actual behavior of a structure under earthquake forces. The results resemble closely how the test underwent, showing the accuracy of the model predicting the actual drifts of the structure.

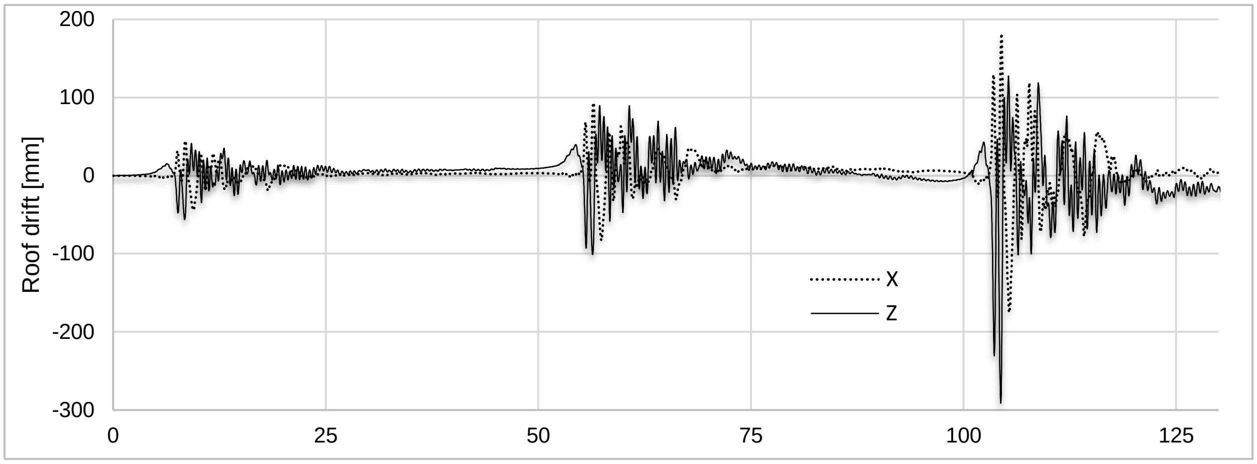


Figure 8: Roof drift results from FEA with Kobe 25%, 50%, and 100%

4 CONCLUSIONS

This paper presents an approach to modelling complex reinforced concrete structures using finite element analysis that is appropriate for predicting their response under earthquake loading. The most efficient way to create beams and columns is using elements with uniaxial fibers. Element joints where plastic hinges and bond-slip can be present, it has been implemented in OpenSees in the form of a two-directional zero-length element with a hysteretic material. Plates, walls and slabs are modelled with bidimensional elements that can represent the combined action of normal and shear stresses, for the concrete material, a damage material is advised, such as Mazars concrete damage material. Deep beams are modelled using a combination of fiber elements where the behavior is provided by mostly normal stresses, such as the flanges of the beams, and plates where the presence of shear stresses is important, such as the web of the beam and the beam ends.

The deformation given by pure bending is described by the normal deformations of the fiber elements in the sections, on the other hand shear deformations need to be described by different methods, i.e. plate elements instead of fibers for deep beams, piers, etc., or the use of Aggregators in OpenSees, to create more complete sections with shear and torsional resistance.

Bond-slip deformations are significant at the base of the structure, where the columns concentrate the maximum bending moment given by the lateral acceleration, this effect must be accounted for when modelling the base joints of the structure.

Further research is necessary in bidimensional concrete materials for the use in finite element analysis. An accurate material code is needed to describe its actual properties, OpenSees provides materials that approximate this behavior, but the results that these materials show differ from the actual performance of the structure and are complex in their calculations. A damage material is being written in the OpenSees framework that describes in a simpler way the behavior of plain concrete in two and three dimensions.

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