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AN OVERVIEW OF MODELING OF RC SHEAR WALLS: ADVANTAGES AND LIMITATIONS

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ABSTRACT:

Modern multi-story reinforced concrete (RC) structures with RC walls are designed considering severe earthquakes loads, however this does not necessarily mean that the seismic response of the wall members is clearly understood and accurately incorporated in design. A reliable numerical model should simulate both global response of the whole structure and important local behavior of the wall member. Furthermore, the endeavor of accurately modeling the seismic response should require reasonable amount of computational and modelling effort.

This paper is written with the objective of conducting an extensive survey on the chronological development of modeling strategies of RC shear walls. From an earthquake engineering point of view, be classified in three major model scales; micro models, meso-scale models and macro models. The macro models, which are commonly used in practice, were examined in more detail in this study. Advantages and limitations are pointed out to understand which model can be properly used during different modelling approaches.

KEYWORDS: Shear wall analytical model, Coupled shear wall system, Shear wall cycling behavior, Shear wall micro model, Shear wall meso-scale model, Shear wall macro model

1. INTRODUCTION

There have been tremendous developments in the last century in the field of earthquake engineering, thanks to the ever increasing number of large-scale tests, developments on sensors, and of course, increasing capacity of personal computers, allowed researchers to elevate the level of understanding of earthquakes and their effects on structures.

Reinforced concrete has been the main type of construction due to its economical and practical advantages. High level of seismic demands in modern structures are answered using large-section vertical bearing elements, which are RC walls. Walls are often connected to each other by using specifically designed beams, which walls and beams together constitute a “coupling-wall system”. Modern multi-story reinforced concrete (RC) structures with coupled RC walls are designed considering severe earthquakes and wind loads, however the nonlinear response of these walls is still not clearly understood.

A reliable and robust model for incorporating the response of wall members in the overall design should simulate important behavioral characteristics of the RC wall members, such as neutral axis migration, the effect of fluctuating axial force, nonlinear shear behavior, shear-flexure interaction, progressive crack closure, deformation capacity, fluxional strength and stiffness due to transverse reinforcement. The model, on the other hand, should be simple as possible without any need in using empirical approaches, which would make the model case-dependent. Last but not the least, the model would be needed to be calibrated against experimental results. In its latest stage, an appropriate model should be applicable in the widely used engineering design softwares in order to get availability.

2. RC SHEAR WALL MODELS

There are several models that can be found in the literature for the purpose of simulating RC shear wall systems behavior. Some of the major models are listed as in Figure 1, where major models are listed.

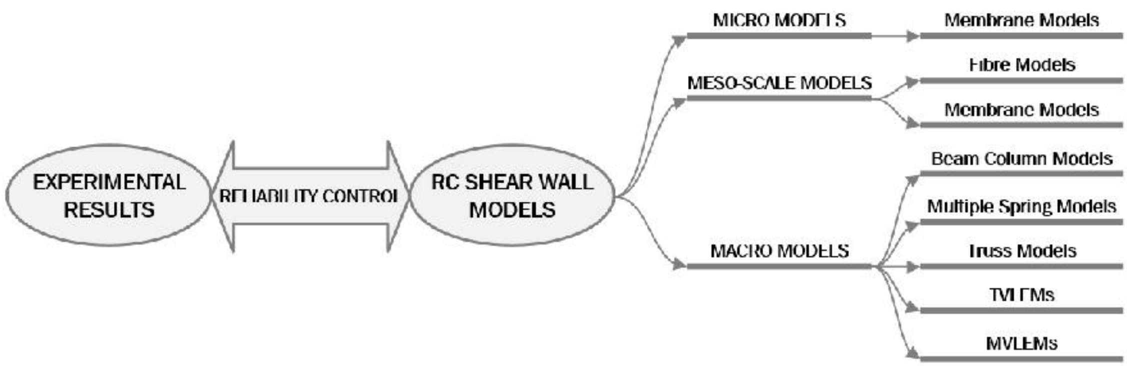

Figure 1 Major RC Shear Wall Models and validation procedure

2.1. Micro Models

Micro models are based on the continuum solid mechanics. The model involves, in-depth, constitutive relations of the concrete and steel. In general, RC wall micro models are built by using finite element method and by assuming that the plane stress conditions are satisfied. However, micro models, which are derived from finite element method discretization for nonlinear analysis of complete frame-wall structures, are practically inapplicable due to complexity (Linde 1993).

2.2. Meso-Scale Models

Meso models placed are between the micro models and the macro models in terms of required computational effort and details required. The model can consist of either two dimensional membrane elements or one dimensional fiber model with simple materials models (Linde 1993), (Martinelli 2007). Especially last two decades, fibre models are widely used in research (Petrangeli et al. 1999) and (Saritas and Filippou 2013).

2.3. Macro Models

2.3.1. Beam-Column Element Models

Beam-column models are characterized by nonlinear bending behavior with moment-axial force interaction. There are various proposed beam-column models with different configurations and hysteresis rules. The shear wall modelling assumption by using beam-column element model, in which the rotations occur about the centroidal axis, is the major limitation. For this reason, the model cannot capture the main behavior characteristics of the wall such as migration of the neutral axis and rocking of the wall.

2.3.1.1.1. Two Component Beam-Column Element

Clough et al. (1965) proposed a two component beam-column element is the first element to be used for modeling of the coupled reinforced concrete (RC) shear walls members. The model consists of shear wall and coupling beams, as given in the Figure . Two Component Beam-Column Element model consists of mainly an elastic component and a perfectly elasto-plastic component to simulate both elasto-plastic behavior and strain hardening. Major limitation of the model developed by Clough et al. (1965) is that the strength degradation cannot be simulated under the cycling load condition.

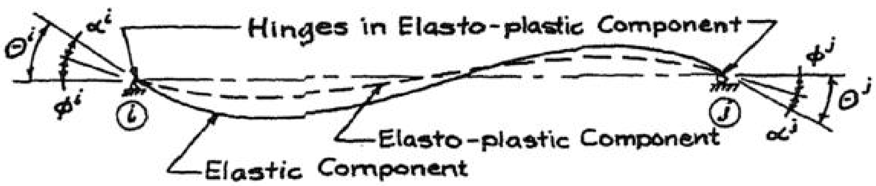

Figure 2 Two component beam column element (Clough et al. 1965)

2.3.1.1.2. One Component Beam-Column Element

Giberson (1967) offered one component beam column element model for the purpose of the modelling elasto-plastic frame structure in him PhD thesis. This model, in fact, is based on series spring analogy. It consists of two components, mainly. The first one is the perfectly elastic beam-column member, which has a length equal the real member length. Second component is the zero-length rotational spring. Two mentioned rotational springs are placed at the ends of an elastic member. Nonlinear behavior of the beam or column can be simulated by using the rotational spring Figure .

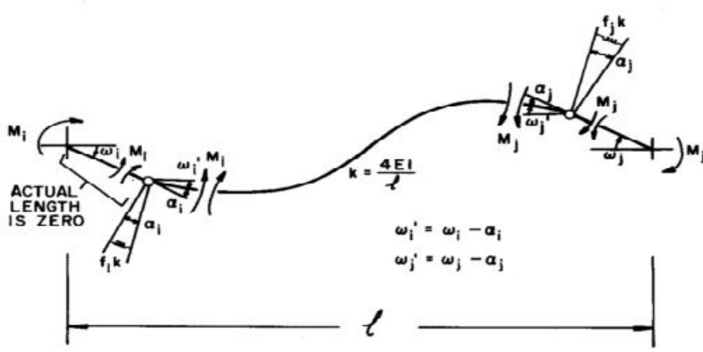

Figure 3 One-component beam-column element (Giberson 1967)

One of the major advantages of this model is that any moment-rotation hysteretic rule can be assigned into the springs. On the other hand, only member-end rotational springs cannot accurately estimate rotations along the member because different nonlinear curvature distribution occurs in case of different zero-moment points, as shown in Figure.

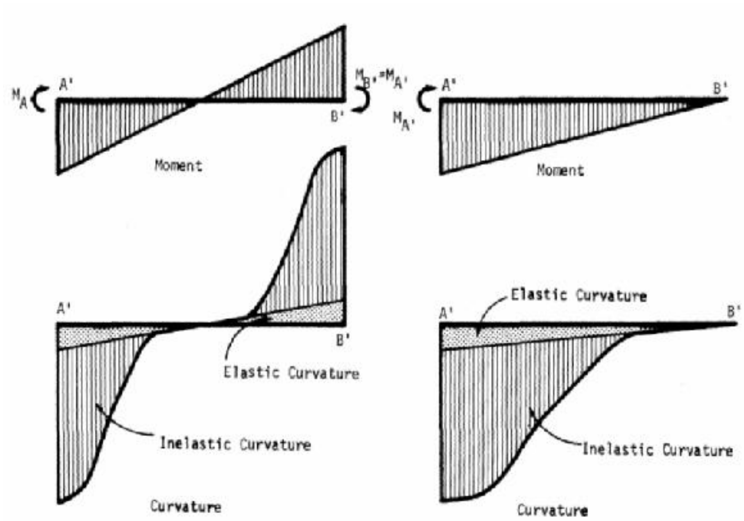

Figure 4 Inelastic moment-curvature distribution for two different cases (Otani 1980)

The stiffness of rotational spring is defined by using the assumption that the contraflexure point is at midspan, due to asymmetric moment distribution as shown in Figure . However, once yielding occurs at the member-end, curvature distribution and contraflexure point changes. Hence, midspan assumption is not valid, but it can be used in practical modeling approach, for the sake of simplicity, particularly in the case of low-rise buildings that the contraflexure point of columns or structural walls locates relatively close to midheight (Otani 1980).

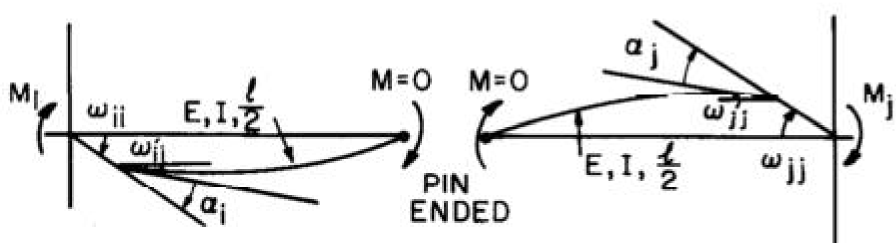

Figure 5 Contraflexure point at midspan assumption (Giberson 1967).

Inelastic shear strain effect on both the member-end rotation and response of the member cannot be taken into account using One Component Beam Column Element modelling approach. Besides, another type of the One Component Beam Column Element model with nonlinear axial spring is also based on the same analogy that is given in Figure . This model includes nonlinear axial spring in order to take into account axial deformation in the elastic element of a column member. One of the main limitations of these models is that the fluctuations of the neutral axis cannot be traced, since the rotation only occurs around the wall centroidal axis.

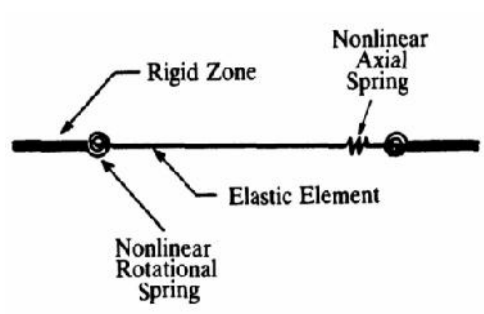

Figure 6 One Component Beam Column Element Model (Kabeyasawa and Shiohara 1983)

2.3.2. Multiple Spring Models

The multiple spring model was proposed by Takayanagi and Schnobrich (1976). This model, in fact, depends on series spring analogy. The model consists of many inelastic springs, connected with each other using rigid members, as shown in Figure . This model breaks down the member to the segments to take into account of severe nonlinear behavior of each column. Each spring represents segment properties that are constant along the segment length. For that reason, walls at the lower stories are divided into more segments than the upper ones. Although this model exhibited adequate results in the studies presented in the literature, it has many drawbacks, such as the fact that the model cannot simulate neutral axis shifting behavior during the flexural bending. The model is also not capable of representing inelastic shear strain effect, bond slip behavior, cracking, changing tension and compression stiffness at the member edge. The effect of all these parameters, which are missing from the model, on the overall behavior is also important and should be investigated.

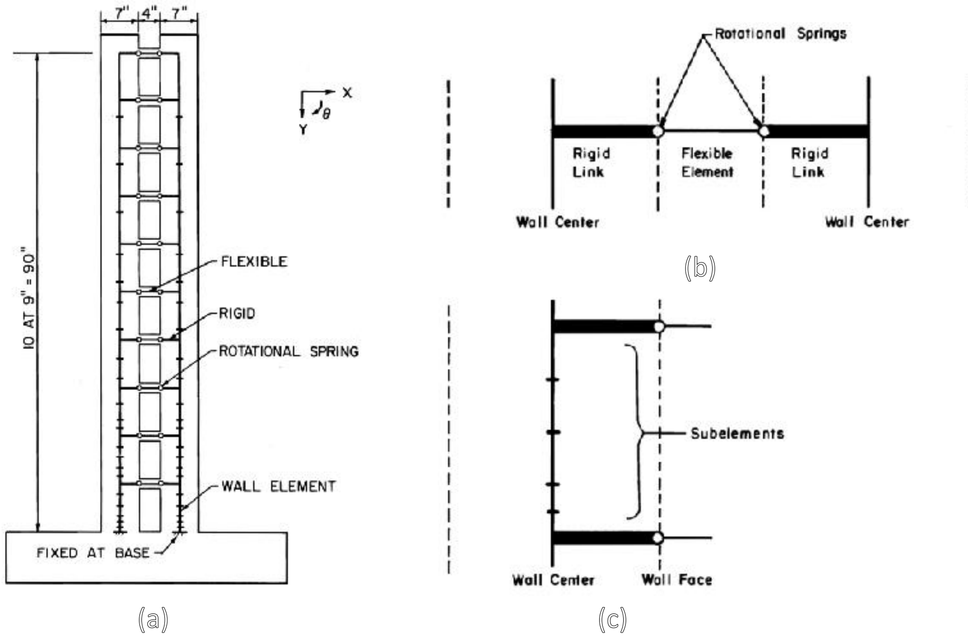

Figure 7 Multiple Spring Model (Takayanagi and Schnobrich 1976), (a) Mechanical Model of Coupled Shear Wall System, (b) Connecting Beam Model, (c) Wall Member Model

2.3.3. Truss Models

Vallenas et al. proposed truss modeling approach after 1/3 scale structural RC wall with monotonic loading conditions (Vallenas et al. 1979). Truss element modelling approaches, such as the strut-and-tie approximation, are frequently used for deep beams and squat shear walls, where a diagonal compression zone inherently develops. The models consist of one-dimensional solid elements together with struts. This type of models generally consist of horizontal tension ties in order to represent the shear reinforcement. Diagonal compression struts are also placed to symbolize the concrete behavior. Finally, two boundary elements are used at the wall edges to satisfy the moment resisting behavior. However, once the alteration of compression and tension forces start, due to the cycling natural of the loading, these struts cannot adequately simulate the actual behavior. Figure explains in general the concept of truss modelling.

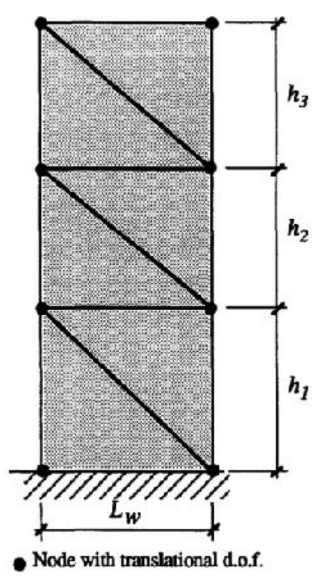

Figure 8 Typical Truss Element Modeling Approach for RC Wall (Linde 1993)

2.3.4. Three Vertical Line Elements Models (TVLEMs)

Three Vertical Line Element Model is a variation of the multiple spring model proposed by Kabeyasawa et al. (1983) within the framework of US-Japan Cooperative Earthquake Research Program. Important behavior characteristics, which should be indeed considered during the modelling of RC walls, such as shifting of the neutral axis, large tensile strain along the member edges can be simulated properly by using this approach. The model is consisted of two rigid beams and five nonlinear springs. Two vertical springs located at both sides of the model are used to simulate boundary elements, with stiffness K1 and K2. . One vertical spring located at the center is used to simulate shear wall web vertical behavior. A coupled RC wall, exposed to flexural behavior, exhibits large elongation along the tension-side boundary element because of cracking. However, compression of the compression-side element induces smaller strains. Hence, flexural deformation of a coupled wall begins with the elongation, primarily. Furthermore, other two springs are located at the center intended to represent the rotational and the shear behavior of the web of the RC wall, as shown in Figure . In other words, there is a one-component element consisted of vertical, horizontal and rotational springs at the center. This model can simulate the rocking and cross-section neutral axis shifting behavior, so it can be more suitable for RC walls, which are part of the outrigger system.

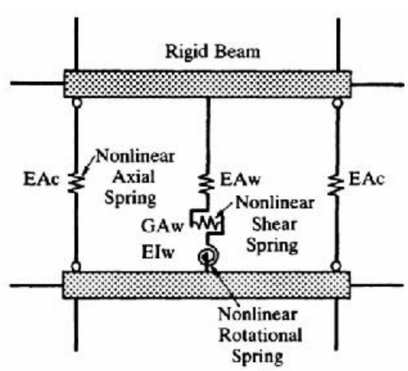

Figure 9 Original macro model (Kabeyasawa and Shiohara 1983)

Origin-Oriented Hysteresis Model (OOHM) was used to simulate both rotational and horizontal springs as shown in Figure . The model dissipates small hysteretic energy why it was selected, mainly. Residual deformation cannot be occurred by using this model and any shape of the skeleton curve can be used.

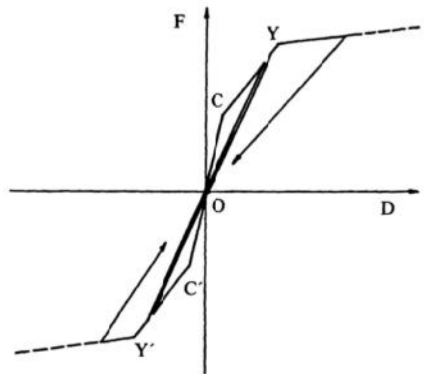

Figure 10 Origin Oriented Hysteresis rule (Kabeyasawa and Shiohara 1983)

Rotational spring properties based on the web response, but the edge vertical springs properties are based on the boundary elements. For this reason, one of the important deficiencies of the model is the compatibility problem arisen from the making an attempt to separate model for flexural and axial behaviors. To overcome this deficiency, Vulcano and Bertero (1987) proposed a softening stiffness approach for the rotational spring and a model known as “Two-Element-in-Series Model” for vertical outer springs as can be seen in the Figure .

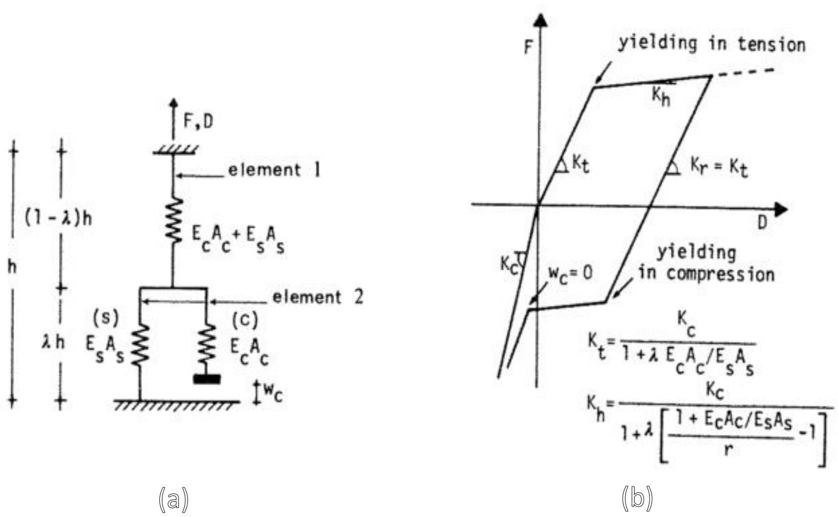

Figure 11 (a) Two-Element-in-Series Model, (b) Simplified Force-Deformation Relationship (SFDR) (Vulcano and Bertero 1987)

2.3.5. Multiple Vertical Line Element Models (MVLEMs)

To overcome the uncertainties stemming from the empirical assumptions used for the especially rotational spring properties, Vulcano et al proposed both Multi-component-in-parallel model (MCPM) and Two-axial-element-in-series model (AESM) as shown is the Figure . The MCPM is also known as Multiple Vertical Line Element Model (MVLEM).

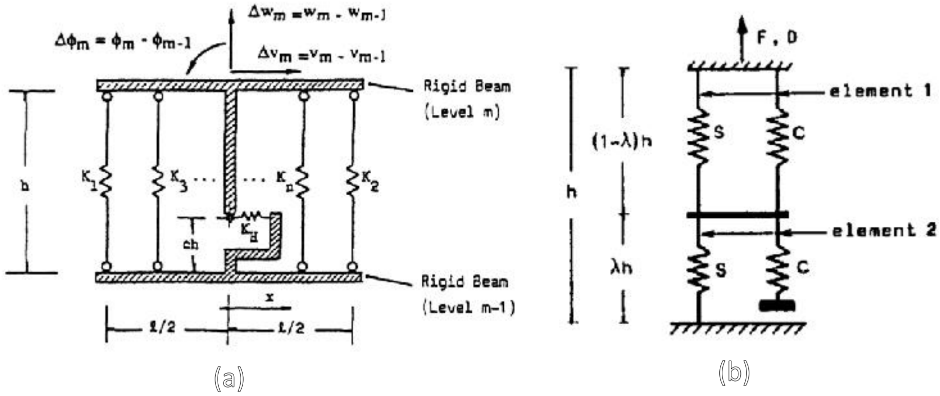

Figure 12 Multi-component-in-parallel model and two-axial-element-in-series model (Vulcano et al. 1988)

MVLEM can simulate many important characteristic behaviors such as migration of the neutral axis, rocking of the wall, refined material behavior, fluctuations in axial load, which are commonly ignored in relatively simple models mentioned before. This model uses a commonly referred assumption that plane-sections-remain-plane by using rigid beams at the top and bottom, like TVLEMs. Vulcano et al. (1988) also suggested OOHM to simulate shear behavior with a horizontal spring. The relative rotation between the two rigid beams occurs around the point placed on the central axis of the element at height c.h as shown in Figure 12 Multi-component-in-parallel model and two-axial-element-in-series model (Vulcano et al. 1988) A value of c was recommended by the authors as 0.4 based on experimental results. The model provides a great deal of accurate prediction when it is applied on the slender walls (Orakcal et al. 2004). Considering only flexural behavior and different state-of-the-art applicable uniaxial material hysteresis rules, it can be said that the model is reasonable.

As it can be seen easily from the model, flexural and shear modes of deformation are uncoupled. However, test results brings into the open that nonlinear shear deformation contribution to wall top lateral displacement ranging from the 20% to 50% according to wall aspect ratio (height-to-length ratio) (Tran 2012). Vulcano and Bertero (1987) also proved that OOHM cannot simulate shear hysteretic behavior under high shear stress condition caused by cycling loading. Hence, reliability of the model for shear behavior became doubtful. Many researcher proposed different models to find a solution to this problem such as (Kabeyasawa 1997), (Chen and Kabeyasawa 2000), (Orakcal et al. 2006), (Kim et al. 2012), (Beyer et al. 2011), (Rejec 2011), (Kolozvari 2013).

Fischinger et al. (1990) proposed different hysteresis rules for vertical and horizontal springs instead of OOHM and SFDR, as shown in Figure 13. However, the model configuration was not modified, they suggested only hysteresis rule for the shear spring. For that reason, engineering judgements play an important role to determine overall behavior by using hysteresis parameters.

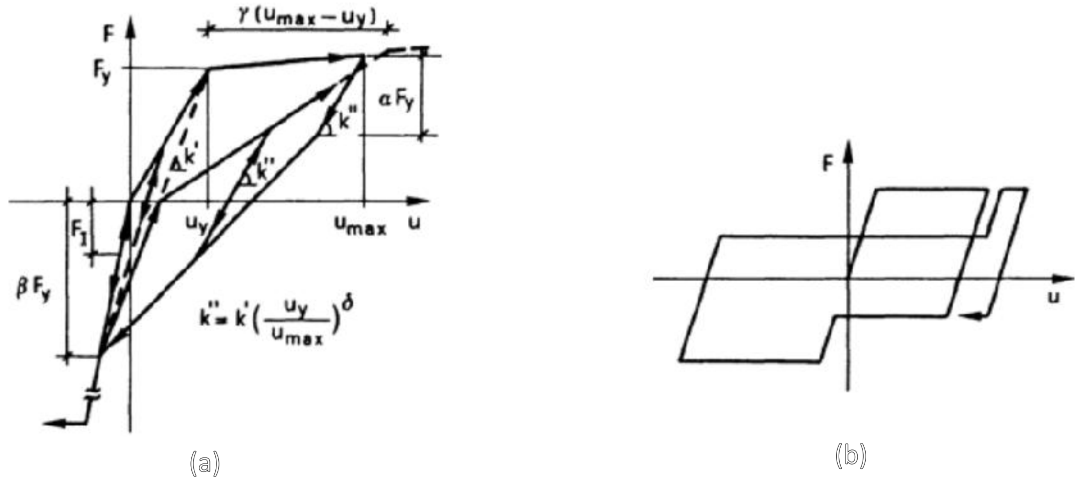

Figure 2 Modified hysteretic behavior rules for vertical (a) and horizontal (b) springs, respectively (Fajfar and Krawinkler 1992).

Kabeyasawa (1997) purposed some modification in the TVLEM to improve the prediction of the overall response (shear and flexural) of RC structural walls for both monotonic and reversed cyclic loading. Central elements such as vertical, horizontal and rotational spring is replaced by one two-dimensional non-linear panel element as in the Figure . Boundary beams and edge columns were modeled in the same manner as in the TVLEM.

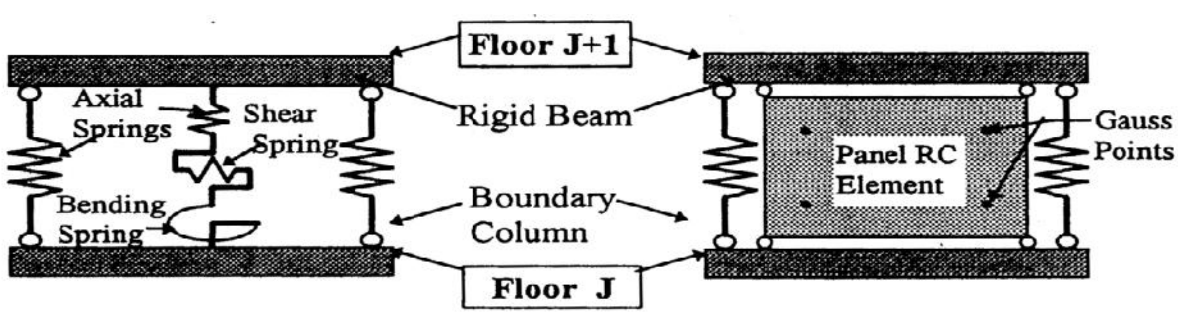

Figure 14 Three-Vertical-Line-Element and Panel-Macro-Element (PMA) (Kabeyasawa 1997)

Kabeyasawa and Chen (2000) used both isoparametric and incompatible (flexural deformation can be introduced) element for central non-linear panel element to compare results. However, one of the main deficiencies of the model is simulation of the concrete shear response as a function of axial load (Orakcal et al. 2006). Numerical and experimental studies was conducted by (Lee et al. 2011) in order to elucidate shear dominant failure mechanism by using both isoparametric model and their prosed model which is suggested for only column member.

Orakcal et al. (2006) applied a methodology which was proposed by Petrangeli et al. (Petrangeli et al. 1999), (Petrangeli 1999) to the multiple vertical line element. Any vertical element considered as a panel element with membrane actions, i.e., shear spring assigned to the each of the vertical line elements as shown in the Figure 15. As a result of this, interaction between flexure and shear is incorporated at the any fiber level. The constitutive panel behavior was represented by using rotating-angle modeling approach.

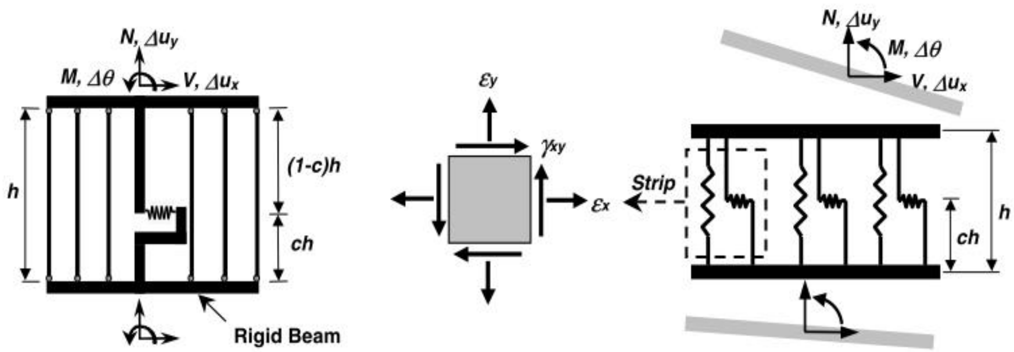

Figure 3 MVLEM and proposed Coupled MVLEM, respectively (Orakcal et al., 2006)

Beyer et al. (2011) proposed empirical relations (shear - flexure displacement ratio (Δ_s/Δ_f) to determine the degree of internal force interaction derived from test results (Beyer et al. 2011), (Mergos and Beyer 2013).

MVLEM was modified by using horizontal spring with each vertical spring like Orakcal et al (2006) model analogy in order to take into account axial-shear-flexure interaction by Rejec (Rejec 2011). Each horizontal spring properties are established semi-empirically considering shear strength that comprised of three component: aggregate interlock, dowel effect and the shear/horizontal reinforcement mechanisms effect as described in the Figure 16.

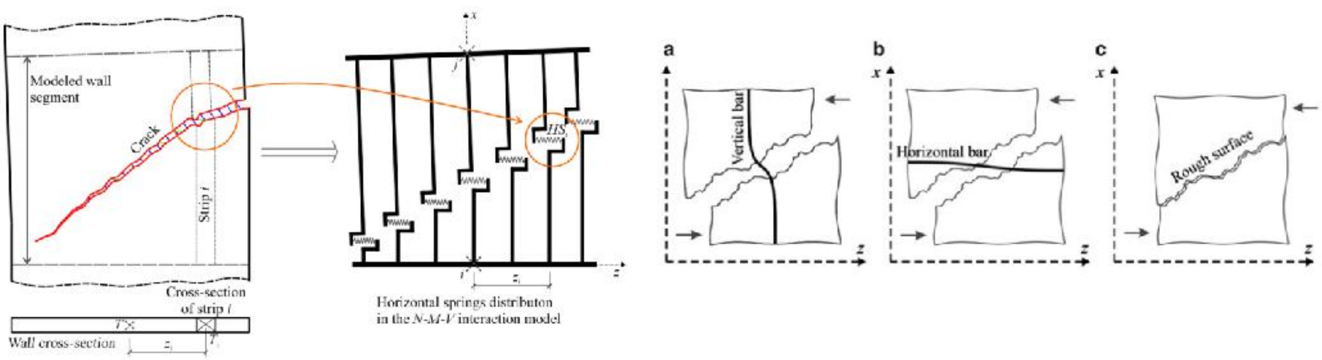

Figure 4 Mechanisms of shear force transfer across the cracks: (a) the dowel effect of the vertical reinforcement; (b) the axial resistance of the horizontal/shear reinforcement, and (c) aggregate interlock in the crack (Fischinger et al. 2014)

Ulugtekin (2010) suggested a constitutive model to simulate cycling shear behavior of RC panel elements. Main assumption of the new constitutive model is that principal stress directions in concrete do not change (rotate) and coincide with fixed (assumed) crack directions, adopting zero shear stresses along the cracks (Ulugtekin 2010).

Kolozvari (2013) proposed a modeling technique by using fixed-strut-angle approach into a two dimensional fiber-based macroscopic model in the PhD. thesis. In this study, effect of material constitutive parameters, aspect ratio, boundary and web reinforcement ratios were investigated parametrically by using of both test and analysis results to validate the model (Kolozvari 2013).

3. CONCLUSIONS

The main goal of the presented study is to introduce the state-of-the art and the recent developments of the RC shear wall modelling approaches for cyclic loading cases. Several models have been presented in the study. Each model is able to capture a part of the overall behavior by ignoring some of the issues. In cases the ignored issues are important in the overall response, the models deviate from the actual behavior. Some models are better than the others and capable of being generalized, however models are not yet mature enough to capture the entire response accurately enough. The study will continue by trying to enhance our understanding of the models capabilities and limitations. Further research is planned to be undertaken by using the models that can simulate the shear-flexure interaction and by conducting parametric studies to better underline the limitations and capabilities of each model, by using the available test data.

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