International Journal of Engineering and Technical Research (IJETR)
ISSN: 2321-0869 (O) 2454-4698 (P), Volume-10, Issue-4, April 2020

Dynamic Behavior of Reinforced Concrete Shear Walls: A Survey

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Abstract—**The reinforced concrete buildings are subjected to lateral loads due to wind and earthquake and these forces are predominant especially in tall and slender buildings. In order to resist these lateral loads, shear walls are provided in the building as a lateral load resisting element which inherently possesses sufficient strength and stiffness. In general, the structural response of shear wall strongly depends on the type of loading, aspect ratio of shear wall, size and location of the openings in the shear wall and ductile detailing (strengthening) around the openings of shear walls. The behavior of shear wall remains linearly elastic till certain level of loading; it may not be possible for a shear wall to behave in a same fashion throughout the loading history.**

Shear walls may be provided with openings due to functional requirement of the building. The size and location of opening may play a significant role in the response of shear walls. Though it is a well-known fact that size of openings affects the structural response of shear walls significantly, there is no clear consensus on the behavior of shear walls under different opening locations.In this paper, we study the behavior of reinforced concrete shear walls under various opening locations using nonlinear finite element.

Index Terms—Reinforced concrete, Shear wall, strength, Shell Element, Material Modeling

I. INTRODUCTION

In the 21st century, there has been the tremendous growth in the infrastructure development in the developing countries, especially India, in terms of construction of buildings, bridges and industries etc. This infrastructure development is mainly due to the growing population and to fulfill their demands. Since the land is limited, there is a huge scarcity of land in urban cities. To overcome this problem tall and slender multi-storied buildings are constructed. There is a high possibility that such structures are subjected to huge lateral loads. These lateral loads are generated either due to wind blowing against the building or due to inertia forces induced by ground shaking (excitation) which tends to snap the building in shear and push it over in bending. In the framed buildings, the vertical loads are resisted by frames only, however, the lateral resistance is provided by the infill wall panels.

For the framed buildings taller than 10-stories, frame action obtained by the interaction of slabs and columns is not adequate to give required lateral stiffness [1] and hence the framed structures become an uneconomical solution for tall buildings. The lateral forces due to wind and earthquake are generally resisted by the use of shear wall system, which is one of the most efficient methods of maintaining the lateral stability of tall buildings. In practice, shear walls are provided in most of the commercial and residential buildings up to thirty stores beyond which tubular structures are recommended.

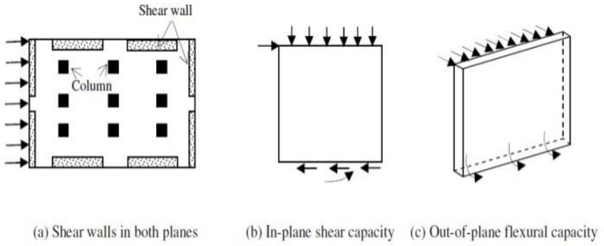

Figure 1: Building plan configuration of shear wall

Shear walls may be provided in one plane or in both planes. The typical shear wall system with shear walls located in both the planes and subjected to lateral loads is shown in Figure 1(a). In such cases, the columns are primarily designed to resist gravity loads. The shear walls are expected to resist large lateral loads (due to earthquake or wind) that may strike “in-plane” [Figure 1(b)] and “out-of-plane” [Figure 1(c)] to the wall. The in-plane shear resistance of the shear wall can be estimated by subjecting the wall to the lateral loads as shown in Figure 1(b). On the other hand, the flexural capacity can be estimated by subjecting the shear wall to the out-of-plane lateral loads as shown in Figure 1(c).

During extreme earthquake ground motions, the response of a structure is dependent upon the amount of seismic energy fed in and how this energy is consumed. Since the elastic capacity of the structure is limited by the material strength, survival generally relies on the ductility of the structure to dissipate energy. At higher loads, inelastic deformation arises which are permanent and imply some damage. The damages generally vary from minor cracks to major deterioration of structure, which may be beyond repair. It has been learnt from past experiences that the shear wall buildings exhibit excellent performance during the severe ground motion due to stiff behavior at service loads and ductile behavior at higher loads thus preventing the major damage to the RC buildings [2]. The behavior of shear wall can be ascertained well by observing the deflected shape. The deflected shape of the tall shear wall is dominated by flexure and that of short shear walls by shear as shown in Figure 2.

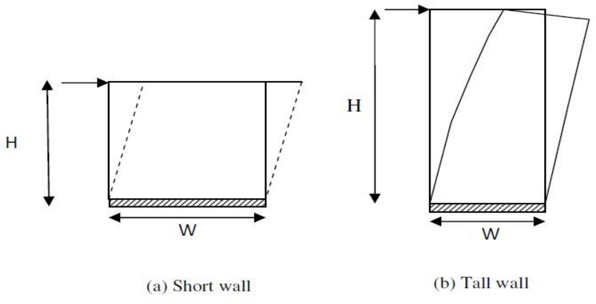

Figure 2: In-plane deformation of shear wall

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II. LITERATURE REVIEW

Literature survey interprets old information and generates a combination of new information with old information. So, in this section there is a brief description of various research papers and occurrence of summary and synthesis of research papers.

Shear walls have been usually adopted as the lateral load resisting elements in Reinforced Concrete (RC) buildings. Since 1940s, a significant number of experimental investigations have been conducted in many countries on RC shear walls. The first experimental investigation on shear walls appears to have been conducted by Ban (1943). Most of these investigations focused on the determination of ultimate strength of walls subjected to various loading conditions such as monotonic, cyclic, dynamic and blast (high-speed monotonic). Significant experimental investigations on shear wall subjected to monotonic loading were conducted at Massachusetts Institute of Technology (MIT), USA in 1949 to develop design procedures for shear-wall structures as well as to prepare a basis for the evaluation of existing shear wall structures. In continuation to the above experimental investigations conducted at MIT, Benjamin and Williams (1953,1954) studied the behavior of RC shear walls surrounded by RC frames under monotonic loading to develop the analytical procedures for the design of shear wall framed structures, The major design variables considered in their study were aspect ratio, reinforcement ratio, and openings etc.

In order to simulate the dynamic loading, in the 1970s, the dynamic loading began to replace the monotonic tests. The first dynamic tests on shear wall were conducted in early 1980s at the Los Alamos National Laboratory (LANL) in the United States using earthquake-simulator. Since then, many experimental and analytical investigations have been performed to determine the responses of shear walls under various loading conditions (Yanez, 1993; Kwak and He, 2001; Fragomeni, 2012).

Lindeburg and Baradar (2001) developed the simplified hand calculation method to analyze the shear walls with openings with varying assumptions (Lindeburg and Baradar, 2001). The accuracy of this simplified method was checked by Neuenhofer (2006) using the linear elastic finite element model of shear wall with conventional four-noded plane stress elements and observed that simplified method consistently underestimates the impact of the openings on the stiffness reduction, thus producing a lateral stiffness larger than that obtained using finite element analysis. Moreover, simplified methods have been found to produce remarkably poor results for shear walls with small aspect ratios where shear deformation controls the structural behavior (Neuenhofer, 2006). Hence, a more versatile method of analysis like finite element method is sought for the analysis of shear wall with varying geometry and subjected to different loading conditions.

The use of shell elements to model moderately thick structures like shear wall is well documented in the literature (Dvorkin and Bathe, 1984). Nevertheless, the general shell theory based on the classical approach has been found to be complex in the finite element formulation. In order to reduce the number of nodes, it was proposed to use degenerated shell element with nodes situated only at the mid plane of the element (Ahmad et al. 1970). The degenerated shell element derived from the three-dimensional element, has been quite successful in modeling moderately thick structures because of their simplicity and circumvents the use of classical shell theory. However, in the case of thin shells, the shear and membrane locking appeared to be disturbing the solutions.

Farvashany et al. (2008) conducted an experimental investigations on seven shear wall models each comprised two beams, one at the top and one at the bottom, and a shear wall panel bounded by two boundary elements to assess the influence of horizontal as well as vertical reinforcement on strength and deformation of high-strength RC shear walls. The tested shear walls with the aspect ratio of 1.57 were scaled approximately to 1/3rd of those in a real building and had a thickness of 76.2 mm (3 in), with a width of 701.04 mm (27.6 in) and a height of 1099.82 mm (43.3 in). The dimensions of edge columns (boundary elements) were 375.92 × 88.9 mm (14.8 in 3.5 in) with the same height of 1099.82 mm (43 in). The purpose of the top beam of size 1300.42 mm × 200.66 mm × 574.04 mm (51.2 in × 7.9 in × 22.6 in) and bottom beam of size 1800.86 mm 299.72 mm × 574.04 mm (70.9 in × 11.8 × 22.6 in) is to resist the stresses in the top and bottom portions, respectively. The two different amounts of horizontal reinforcement of 0.47% and 0.75% were used in conjunction with two different amounts of vertical reinforcement of 1.26% and 0.75%. The reinforcement ratio used for boundary elements in all specimens was kept at 4%. They observed that the increase in vertical reinforcement ratio increases the horizontal failure load. On the other hand, the effect of horizontal steel ratio was found to be not as significant as the vertical steel ratio. The shear strength of the shear wall was found to be increased only marginally with an increase in horizontal steel ratio.

Fragomeni et al. (2012) pointed out that the design of shear walls with openings is being given little importance in International codes of practice despite several experimental and analytical investigations.

For the analysis of shear wall, several analytical methods have been proposed by various researchers which range from simplified conventional approach to the sophisticated finite element approach.

III. METHODS OF ANALYSIS OF SHEAR WALL

In the early days, several conventional analytical methods were developed and adopted for the elastic analysis, specifically to shear wall. The popular conventional methods may be enumerated as (i) Continuous Connection Method, (ii) Transfer Matrix Method, (iii) Wide Column Analogy or frame analysis, (iv)Discrete Force Method, etc. Nevertheless, these methods involve assumptions of linear elasticity and cannot be programmed to handle complex problems, especially under severe earthquake ground motion. The Finite Element Method (FEM) has been the most versatile andsuccessfully employed method of analysis to accurately predict the structural behaviorof reinforced concrete shear walls in linear as well as in non-linear range under staticand dynamic loading conditions. The analytical procedures of the shear wall may bebroadly categorized into (i) Linear Elastic Procedure, (ii) Linear Dynamic Procedure,(iii) Non-linear Static Procedure, and (iv) Non-linear Dynamic Procedure.

(a) Linear elastic procedure

In earlier days, the analyses of RC shear walls were based on the fact that the concrete remains un-cracked and hence the linear elastic behavior was followed in predicting the response. Michael et al. (1970) used linear elastic finite element analysis with substructure approach to analyze the shear walls with and without openings and observed that the finite element results were in good agreement with experimental results in the linear elastic range (Michael et al. 1970). Petersson and Popov (1976) developed a special purpose finite element computer program for the analysis and design of structural walls with and without openings. This computer program was capable of predicting the behavior of structural walls with multiple openings.

Nevertheless, several building codes including International Building Code (IBC 2000) considers the use of cracked section and recommends the use of reduced stiffness after the onset of cracking. Sometimes, the reduced stiffness is found to be 75 to 80% of the gross un-cracked cross section's stiffness. This procedure of analysis is incapable of capturing the higher modes of deformation.

(b) Linear dynamic procedure

The linear dynamic procedure incorporates the effect of higher modes of deformation and considers actual distribution of forces in the elastic range in a better way as compared to linear static procedure (Mothei, 2005; Su and Wong, 2007). The use of linear dynamic procedures such as mode superposition and response spectrum method has been found extremely popular for linear systems. Nevertheless, in reality, during strong earthquakes, buildings are generally subjected to large inertia forces, which cause members of buildings to behave in a non-linear manner. In such scenarios, linear analysis fails to capture the actual strength of the structural members, which is only possible with non-linear static or non-linear dynamic analysis procedure (Naeim, 2001).

(c) Non-linear static procedure

The non-linear static procedure is an improvement over the linear static analysis in the sense that it allows the inelastic behavior of the structure. In this method, the magnitude of the structural loading is incrementally increased in accordance with a certain predefined pattern. The non-linear static procedure gives accurate results for structures whose response is dominated by a fundamental mode. This method of analysis neglects the variation of loading with time, the influence of higher modes and the effect of resonance. For structures that are more flexible, the response quantities are strongly influenced by higher modes and hence non-linear static procedure predicts highly inaccurate results for such cases (Mothei, 2005). The non-linear dynamic procedure is the only method to describe the actual behavior of the structure during strong earthquakes (Su and Wong, 2007). This method is based on the direct numerical integration of the differential equation of motion.

(d) Non-linear dynamic procedure

According to D' Alembert's principle, the unbalanced force is proportional to the acceleration of the structure and the constant of proportionality being the mass. Considering the free body diagram of rigid block shown in Figure 1.12, the equation of motion of rigid block of mass 'm' in the lateral direction is given by

$$R(t) - ku - cu = mu \approx m u + c u + k u = R(t) \quad (1)$$

The above equation is the second order linear differential equation with constant coefficients. However for the non-linear case, the above equation is represented as

$$mu + cu + fs\,(u\,,u) = R(t) \quad (2)$$

The constant coefficients *m*, *c* and *k* are the mass, damping and stiffness components respectively and *R*(*t*) is an external force, which varies with time '*t*'. The term *fs* represent the restoring force component which varies with time.

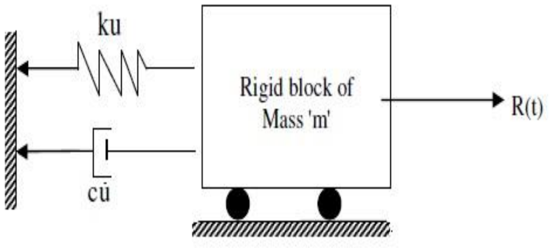

Figure 3: Dynamics of rigid block

In order to define the motion of rigid block of mass m at various time intervals, it is normally suggested to use direct step-by-step time integration. The direct step-by-step time integration is computationally very demanding than response spectrum technique. Mothei (2005) observed that for RC structures, the inelastic time history method has been found to give displacements up to 10% higher than the spectral analysis (Mothei, 2005). The direct integration method is further classified into implicit and explicit methods. Both the methods are extensively used in determining the response of the structure at discrete time intervals.

The various implicit and explicit direct integration methods are well described in the literature (Chopra, 2006; Clough and Penzien, 2003; Bathe, 1996). However, for completeness, the explicit and implicit time integration methods are discussed briefly.

IV. SHEAR WALL WITH OPENINGS

Several experimental and analytical studies confirm that the structural behavior of the shear wall with opening is complex due to stress concentration near the openings (Neuenhofer, 2006), leading to reduction in stiffness and strength of the wall. Moreover, openings in the shear wall result in the reduction in the concrete area and may result in the tremendous shear deformation even in the case of tall slender shear walls. Moreover, the force transfer gets disturbed in the shear wall with openings. The shear strength of the wall with openings should be examined along critical planes that pass through openings. Hence it is necessary to provide proper reinforcement in horizontal as well as in vertical direction around the openings. This vertical and horizontal reinforcement constitutes a steel band around openings thus resulting in strengthening (ductile detailing) of the shear wall. The diagonal reinforcement may also be provided around the openings as a part of strengthening process. The American Building Code Requirements for Structural Concrete (ACI 318-11) specifies that for walls with openings, the influence of the openings on the flexural and shear strengths are to be examined.

Depending upon the size, shape and location of openings, the response of the shear wall may get affected. The Architectural Institute of Japan (AIJ) specifies that the strength reduction factor of a shear wall due to the openings is limited to 0.6 by restricting the maximum ratio of opening dimensions to the corresponding wall dimensions. On the other hand, the seismic code of China specifies that the limiting value of the opening to be 15% of the area of wall. Nevertheless, these limits have been specified only to make the conventional methods applicable to wall structures as well. Most of the other codes are silent on the limiting percentage of openings in shear wall. This is partly due to lack of research on multiple openings in shear wall (AIJ, 2000; Kato, 1995). In order to determine the influence of openings on the structural response of reinforced concrete shear wall, many experimental and analytical investigations have been conducted in the past several decades as portrayed in the next chapter in detail. The research study on the shear wall panel by Tomii and Miyata (1963) revealed that the position of the openings in the shear wall did not greatly influence the response of the shear wall. Nevertheless, recent studies specify that the opening positions affect the performance of the shear wall (Neuenhofer, 2006). It is also suggested that the circular openings result in less severe stress concentration than rectangular openings. Nevertheless, due to practical difficulties as well as due to the complexity in modeling circular shape openings, rectangular/square openings are generally provided and hence have been considered for the present analytical study.

V. MATERIAL MODELING OF RC STRUCTURES

Due to the advantage of its rigidity, RC shear walls which offer great resistance to lateral loads have been widely adopted in building structures as a lateral load resisting element.

The material modeling of RC structures has been the subject of interest for many decades, because incorrect modeling results in poor characterization of its behavior. To cater to the increased demand for seismic design of RC structures, many experimental and analytical studies to capture the nonlinear response of RC structures under extreme loading conditions have been performed. Though the experimental investigation gives the required information close to reality, it is not always a viable alternative as experimental parametric studies incur huge cost and time. On the other hand, the design method envisaged in various codes based on many concepts often underestimates or over-estimates the structural response. Thus, there is a need for a reliable analytical model which predicts the behavior close to real behavior. Non-linear finite element analysis is an established analytical tool to evaluate response of RC structures.

The non-linearity in the reinforced concrete may be due to change in structural and material characteristics and may result in structural cracking of concrete, yielding of concrete and steel and crushing of concrete. Nevertheless, these non-linearities are considered to be instantaneous and assumed to be time independent. Such time independent non-linearities are usually incorporated in the analytical modeling of reinforced concrete. On the other hand, the non-linearity may also be caused due to creep and shrinkage effects which are time dependent. Such time dependent non-linearities are difficult to be incorporated analytically and hence not considered in the present study.

The time independent behavior of materials can be further idealized into elastic behavior and plastic behavior. For an elastic material, there exists a one-to-one coordination between stress and strain. An elastic material is the material which returns to the original shape when the loads are removed. This is the minimal requirement for the material to qualify as elastic. The material which satisfies this minimal requirement is also known as hypo-elastic material. In a more restricted sense, an elastic material must also satisfy the energy equation of thermodynamics. The elastic material characterized by this additional requirement is known as hyper-elastic.

On the other hand, the plastic material is the one in which the reversibility is not satisfied, i.e. the material undergoes some permanent deformation which cannot be retraced even after the removal of loads and stresses. Hence, the strain in the plastic material may be considered as the sum of the reversible elastic strain and the permanent irreversible plastic strain. The stress-strain law for a plastic material reduces, essentially, to a relation involving the current state of stress and strain and the incremental changes of stresses and plastic strains. This relation is generally assumed to be homogeneous and linear in the incremental changes of the components of stress and plastic strain. This assumption precludes viscosity effects, and thus contributes to the time-independent idealization. For the complete modeling of RC, constitutive laws representing elastic and plastic states are to be defined clearly. Elasticity based constitutive laws are required to define the behavior of the material in the elastic state while plasticity based constitutive laws are required to define the behavior of the material in the plastic state.

Furthermore, the development of analytical models to determine the response of RC structures is complicated due to the following three factors: a) Reinforced concrete is a composite material made up of concrete and steel, which have very different physical and mechanical behavior, b) concrete exhibits non-linear behavior even under low level of loading due to cracking of concrete and c) reinforcing steel and concrete interact in a complex way through bond-slip and aggregate interlock. Thus, for the finite element analysis of RC structures such as panels and shear walls, the analytical model must include (i) a strength criterion for concrete subjected to various stress combinations, (ii) concrete cracking and crack propagation, (iii) steel yielding, (iv) concrete crushing, and (v) the tension-stiffening behavior of reinforced concrete through bond-slip.

The modeling of material may play a crucial role in achieving the correct response. The presence of nonlinearity may add another dimension of complexity to it. The nonlinearities in the structure may accurately be estimated and incorporated in the solution algorithm. The accuracy of the solution algorithm depends strongly on the prediction of second-order effects that cause nonlinearities, such as tension stiffening, compression softening, and stress transfer nonlinearities around cracks.

These nonlinearities are usually incorporated in the constitutive modeling of the reinforced concrete. In order to incorporate geometric nonlinearity, the second-order terms of strains are to be included.

VI. CONCLUSION

In this paper we review the behavior of reinforced concrete shear walls. Shear walls may be provided with openings due to functional requirement of the building. The size and location of opening may play a significant role in the response of shear walls.It studied the behavior of shear walls under various opening locations using nonlinear finite element analysis using degenerated shell element with assumed strain approach. This paper concluded methods of shear walls and materials of Reinforced Concrete structure.

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