BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iaşi
Tomul LVI (LX), Fasc. 2, 2010
Secţia
CONSTRUCŢII. ĂRHITECTURĂ

SEISMIC BEHAVIOUR OF REINFORCED CONCRETE SLIT SHEAR WALLS ENERGY DISSIPATORS

BY

SERGIU BĂETU and I. CIONGRADI

Abstract. The types of slit walls energy dissipators, from monolith or precast reinforced concrete, proposed by researchers and the seismic behaviour of these types of walls are described. The overall ductility of the structure increases, considering the energy dissipation solutions proposed by the researchers of the reinforced concrete walls, resulting a supplementary safety for the structure. The objective of these solutions is to create an ideal structure for tall multi-storey buildings, that behaves as a rigid structure at low seismic action and turns into a flexible one in case of a high intensity earthquake action. The solutions for increasing ductility proposed in this paper are viable and easily to use in constructions practice. For the analysis of slit wall, the researchers used a series of analytical calculation methods, among the most important being the equivalent frame method and the finite element method, both presented § **3** of the paper. The researchers concluded that by using this calculations methods, the dynamic behaviour of the reinforced concrete slit walls can be simulated very accurate and realistic.

Key words: energy dissipators walls; ductility; finite element method; equivalent frame method; lateral resistance; ideal structure.

1. Introduction

Reinforced concrete walls are strength and portant elements frequently used in constructions in seismic areas, because they have a high lateral stiffness and resistance to external horizontal loads.

If the wall stiffness is high, the seismic loads taken by the structure become heigher, resulting non-economic sections for the wall. This phenomenon occurs particularly in multi-storey tall buildings. In case of high intensity earthquakes flexible structures are preferred because can accept large deformations, instead for low intensity earthquakes that occur frequently, or for wind action, rigid structures should be considered, because prevent large displacements. The dissipation of the accumulated energy in the stuctural wall systems occurs generally through concentrated degradation at the base of the wall (Fig. 1), which are difficult to repair. For the wall showed in Fig. 1 two negative characteristics are pointed: low ductility and low redundancy.

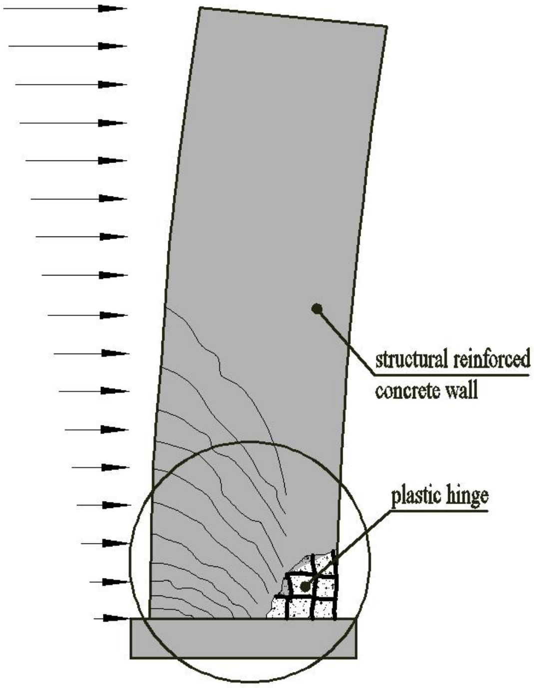


Fig. 1 – Destruction of reinforced concrete walls at horizontal seismic action.

Numerous investigations have been made to improve redundancy and ductility of structural walls exposed at horizontal actions and some practical solutions were proposed. Slit walls are a special variant of structural walls with improved ductility. The specialists intention was to reduce the degradation from the base of the wall and distribute it on the wall height.

The plastic hinge formation furnishes gives to the structure kinetic energy dissipation capacity, but also constitutes a state of structural damage. A performance-based design will ensure the life safety and viable rehabilitation from economical point of view to a building subjected to a major earthquake.

In the followings the composition principles of slit reinforced concrete shear walls is analysed with the purpose to create structures with a high safety level at seismic action.

2. Slit Walls Evolution

A particular reinforced concrete structural wall, with good properties of seismic energy dissipation, called *slit wall*, was patented by Professor K. Muto in Japan, in 1973 [1]. These walls are the first energy dissipation system used in the structures of Japan. The first building made with this system is the Keio Plaza from Tokyo (1968), a 36-storey frame structure made of steel [2]. In the structure frameworks, vertical strips of concrete forming a slit panel are introduced. The contact between the strips is made with plaster, asbestos sheets, synthetic resin or metal plates (Fig. 2). Seismic energy dissipation is achieved by destroying the connection between the reinforced concrete strips. The goal of this invention is to create an ideal structure for high multi-storey buildings, which under reduced seismic actions behaves as a rigid structure and under the action of high intensity earthquakes turns into a flexible one. Initial energy dissipation was achieved by the cracks distribution on a large surface in slit panels.

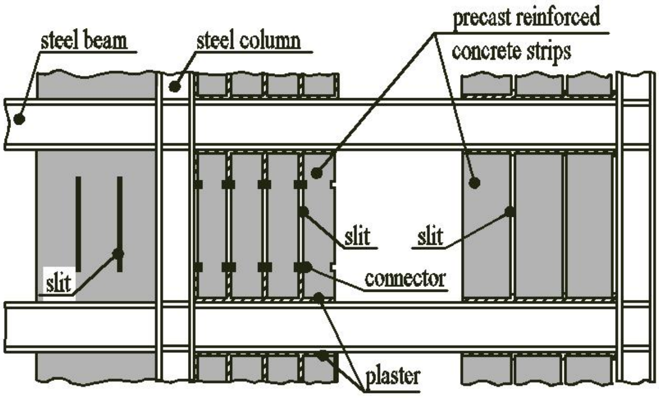


Fig. 2 – Slitted panels.

In Fig. 2 are presented three options for the composition of slit panels: precast reinforced concrete strips, precast reinforced concrete strips attached with connectors and panels with incomplete slits.

Korean researchers have proposed another type of slit wall (Fig. 3), used especially for reinforced concrete structures, in which strips are anchored in beams [3]. Compared with slit walls made of prefabricated strips, these walls have a better ductility, a higher energy dissipation capacity and accept greater lateral displacements. The structural behaviour of these panels is influenced by the concrete properties of the strips, the panel size, the axial loading intensity, the slit thickness and the material added in slit.

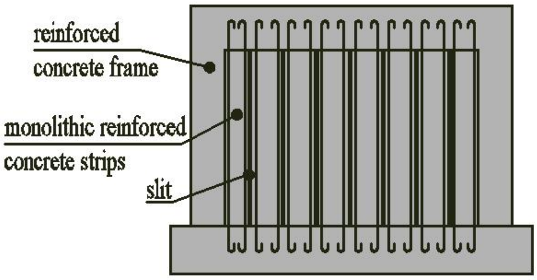
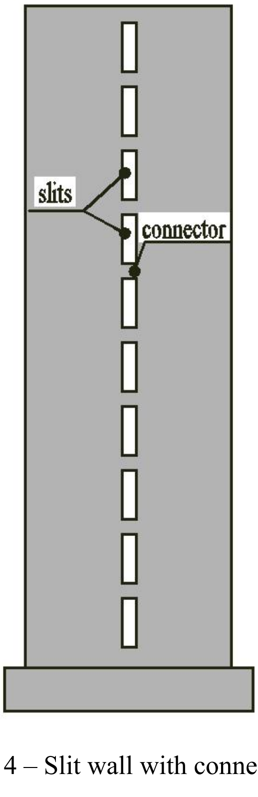


Fig. 3 – Monolith slit panel.

Another type of slit wall is analysed by researchers from Chinese University of Hong Kong (Fig. 4) [4]. Reinforced concrete connections were placed on the slit height which attach the structural walls forming a dissipative zone.



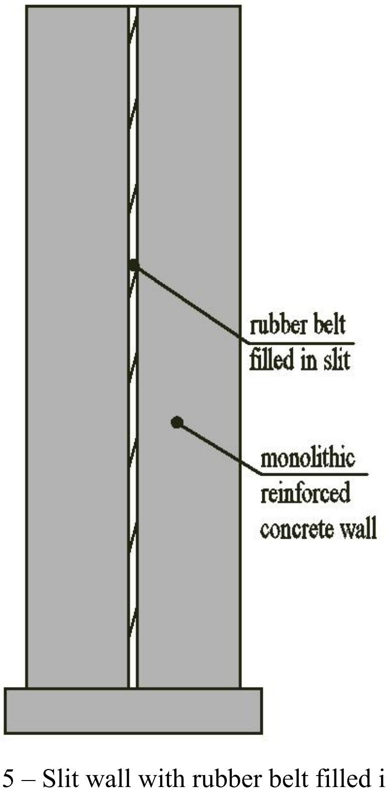


Fig. 4 – Slit wall with connections.

Fig. 5 – Slit wall with rubber belt filled in.

Researches have been conducted in comparison with a solid reinforced concrete wall without slits. Results showed the efficiency of the slit wall: the displacements decreas with 14…25% in case of a cycle loading, reduced drift by 19…26%, the seismic force induced in the wall is reduced by 20…25% and the structure period is also reduced and the overall ductility is improved. Seismic performance depends on the yielding resistance of the connections. An efficient design of these systems must take into account a rational design of the connectors. The premature yielding of the connectors must be avoided and also the destruction of walls without yielding of the connectors.

A slit wall model was proposed at the University of Shanghai, China, by X. Lu and X. Wu [5] [6] in 1996 (Fig. 5). They have inserted between the reinforced concrete strips rubber belts dissipative of kinetic energy. To improve the seismic behavior, at each level of the structure connections with four reinforcement bars which pierce the rubber belt and which are anchored into the wall are made. The system thus formed has a very good ability to dissipate the seismic energy. Seismic energy is dissipated by the elastic rubber deformation,

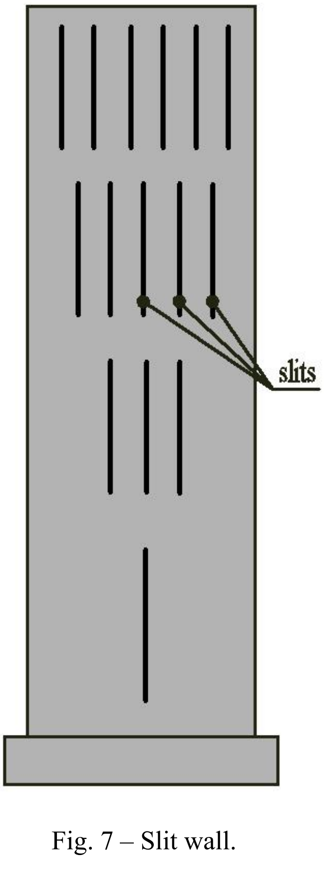


Fig. 7 – Slit wall.

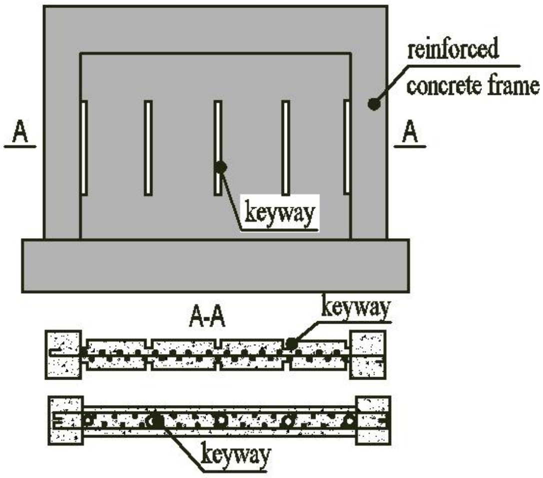


Fig. 6 – Wall with vertical keyways.

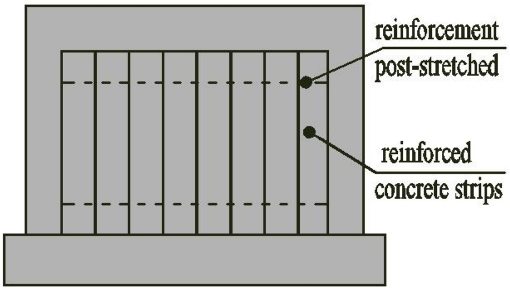


Fig. 8 – Panel made of strips assembled by post-stressing.

the yielding of the reinforcements from the connections and the friction between concrete and rubber strap.This type of slit wall is considered an improvement of previous presented versions, with connectors made of reinforced concrete, because the destruction is less and the energy dissipation capacity is increased. Considering this structural solution were built two buildings with 38 floors in Shanghai, in 1997.

In order to increase the amount of energy dissipated by a reinforced concrete wall, researchers at the University of Tehran have examined other slit wall (Fig. 7) [7]. They introduced a large number of slits at the top of the structural wall and a reduced number of slits at the base. In this case failure results from the action of shear force on each strip. If the number of slits increases the structural wall behaves more ductile and the number of plastic hinges is higher, resulting an increase of the energy dissipated by the wall height.

A wall with vertical keyway was investigated in China (Fig. 6), the basic principle being that of the slit walls [8]. These walls have greater strength than a slit wall, smaller displacements and lower ductility. Kinetic energy dissipation is achieved by the concrete cracking in the vertical keyways.

Russian researchers have patented an energy absorbing panel made of strips assembled by post-stressing (Fig. 8). The energy dissipation is achieved by the friction between the strips [9].

3. Analytical Methods for the Slit Walls Design

For the analysis of slit wall, the researchers used a series of computation methods, among the most important being *the equivalent frame method* and *the finite element method.*

3.1. Equivalent Frame Method

The equivalent frame method is used to design slit walls with reinforced concrete short connections [4]. Structural walls are modeled as columns and connections are modeled as flexible beams in slit region and as infinite rigid beams in the wall region (Fig. 9). For the analysis of the structural system a standard frame program is used. In the analysis the nonlinear inelastic behavior of the connections is accepted while for the columns the linear–elastic behavior is taken into acount, because it is considered that the walls are not degraded by the seismic action. Equivalent frame method used to design reinforced concrete slit walls with connections has the advantages that is simple, easily to understand and allows a more faster analysis compared with the finite element method. The analysis of a structural slit wall model through the presented two methods – finite element method and equivalent frame method –

shows that differences between the numerical results are 2…3%, finite element method being more accurate.

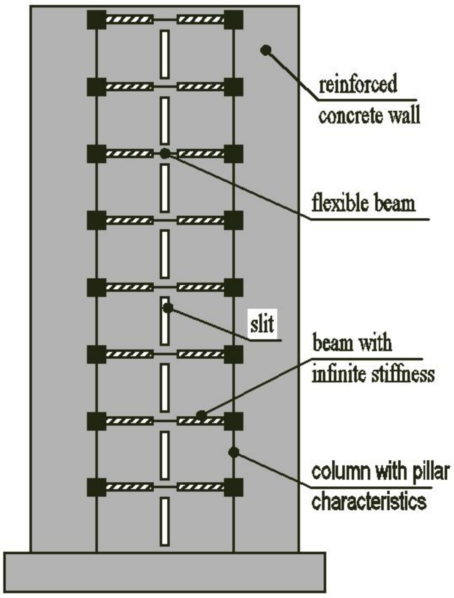


Fig. 9 – Equivalent frame method for slit wall with connections.

Step integration method Newmark-β is commonly used by researchers for nonlinear dynamic analysis to obtain the dynamic equation of motion solutions. To obtain an accurately dynamic response of the structure, the time step must be below 1 ms. The dynamic equation of motion at any time, *t*, is written incrementally in the following form:

$$M\Delta\ddot{u} + C\Delta\dot{u} + K\Delta u = \Delta p(t), \tag{1}$$

where: M is mass matrix of the structure; $C = \alpha M + \beta K$ – damping matrix of the structure; α, β – specific parameters Newmark-β integration method; K – stiffness matrix of the structure; $\Delta\ddot{u}, \Delta\dot{u}, \Delta u$ – vectors of incremental nodal acceleration, velocity and displacement, respectively; $\Delta p(t) = -M\Delta\ddot{u}_g(t)$ – incremental vector of applied load; $\Delta\ddot{u}_g(t)$ – incremental vector of ground acceleration.

3.2. Finite Element Method

The principle of finite element method (FEM) analysis consists in decomposition of the domain in parts of simple geometric shape, analysis and field recomposition that respect certain physical and mechanical requirements.

To simulate the seismic behavior of the reinforced concrete walls, the researchers are using several finite element programs such as Ansys, Etabs, Robot Millennium, etc.

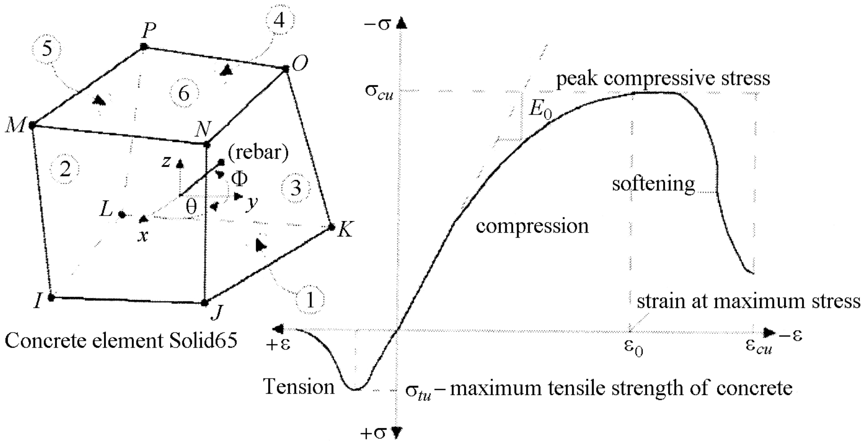


Fig. 10 – Finite element Solid65 and concrete compressive and tensile curve.

For modeling concrete in Ansys is used a solid with 8 nodes [10] [11], Solid65 (Fig. 10). Researchers showed that concrete simulations with this element are very accurate.

The curve shown in Fig. 10 corresponds to compression and stretching of the concrete [12]. The stress–strain compression curve for concrete is linear–elastic up to 30% of the maximum compression pressure. After this value, it reaches the maximum compression pressure, σ_{cu} , the curve decreases, failure occuring to the last deflection, ε_{cu} . In stretching, the stress–strain curve for concrete is approximately linear–elastic up to the maximum tensile stress, σ_{tu} . After this point, the concrete cracks and the tension decreases up to zero.

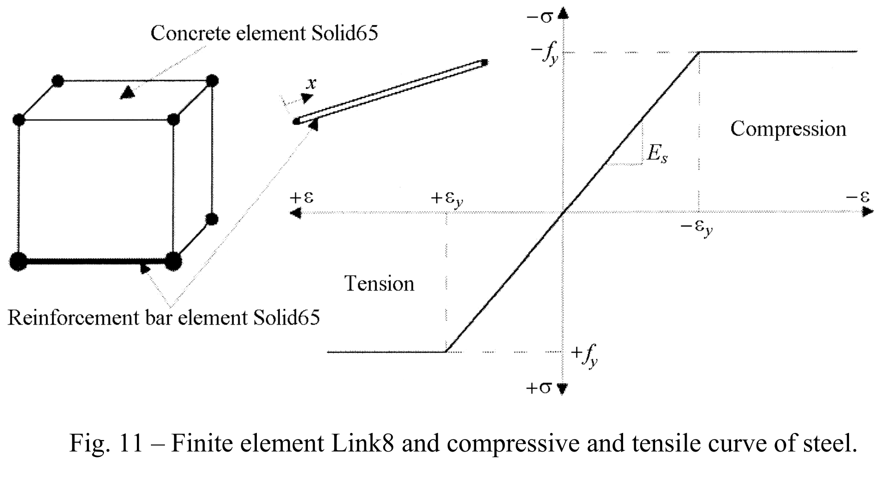


Fig. 11 – Finite element Link8 and compressive and tensile curve of steel.

In Ansys, steel reinforcement bars used to reinforce the wall structure are modeled with individual finite element bar type, being used Link8 element (Fig. 11), or with distributed elements in concrete structure. Reinforcement distribution in concrete structure is used for simplification, entering the reinforcement percentage and the steel properties on each direction. Link8 element [12] has two nodes and each node has three degrees of freedom, translations after. Element can have plastic deformation.

Steel finite elements Link8 have identical behavior in compression and in tension (Fig. 11). The material is considered elastic–perfectly plastic.

4. Conclusions

An economical design of buildings based on performance takes into account the dissipation of seismic energy accumulated in the structure. Reinforced concrete walls are frequently used as strength elements for structures designed in areas with high seismic risk. The main problems of these structural elements – low ductility and redundancy – are removed through the solutions proposed in this paper. Research has shown remarkable improvement of the structural slit walls, very good seismic behavior, stable hysteretic curves with high kinetic energy dissipation. The calculation methods presented in the paper – equivalent frame method and finite element method – are the most frequently used to design structural slit wall, investigations performed have shown comparable results in practical experimental models.

Received, October 14, 2009

"Gheorghe Asachi" Technical University of Iaşi,
Department of Structural Mechanics
e-mail: sergiubaetu@yahoo.com

REFERENCES

1. Muto K., Ohmori N., Itoh T., *Composite Building Structure and Walls therefore*. USA Patent *3736712* (1973).
2. Aoyama H., *Dr. Kiyoshi Muto (1903-1989)*. Struct. Engng Internat. J. 50-52 (2005).
3. Liou Y.W., Sheu S.M., *Prediction of Lateral Stiffness for Fully Slitted RC Shear Wall*. J. of the Chinese Inst. of Eng., **21**, 221-232 (1998).
4. Kwan A.K.H., Dai H., Cheung Y.K., *Non-Linear Sesimic Responce of Reinforced Concrete Slit Shear Walls*. J. of Sound a. Vibr., *226*, 701-718 (1999).
5. Lu X., Wu X., *Study on a New Shear Wall System with Shaking Table Test and Finite Element Analysis*. Eartquake Engng. a. Struct. Dyn., **29**, 1425-1440 (2000).
6. Lu X., Huanjun J., *Non-Linear Eartquake Response Analysis and Energy Calculation for Seismic Slit Shear Wall Structures*. Eartquake Engng. a. Engng. Vibr. J., **1**, *2*, 227-237 (2002).
7. Sabouri J., Ziyaeifar M., *Shear Walls with Dispersed Input Energy Dissipation Potential*. Asian J. of Civil Engng. (Building and Housing), **10**, 593-609 (2009).
8. Ding J.D., Dai H., Xia X.D., *Aseismic Constructions and Design Method for Multi-Storey Composite Structures*. Eartquake Engng. a. Struct. Dynamics, **25,** 887-907 (1996).

9. Pavlik V.S., Vasionkin A.N., *Earthquake Resistant Building*. Patent SSSR *512279* (1976).
10. Raongjant W., Jing M., *Finite Element Analysis on Lightweight Reinforced Concrete Shear Walls with Different Web Reinforcement*. The Sixth PSU Engng. Conf., May 8-9, 2008, 61-67.
11. Khezroddin A., Naderpour H., *Non-Liniear Finite Element Analisys of Composite RC Shear Walls*. Iranian J. of Sci. & Technol., Trans. B, Engng., **32,** 79-89 (2008).
12. Kachlakev D., Miller T., Yim S., *Finite Element Modeling of Reinforced Concrete Structures Strengthened with frp Laminates*. Oregon Dept. of Transp., USA, Res. Group, Final Report SPR 316, May 2001.

COMPORTAREA SEISMICĂ A PEREȚILOR ŞLIȚAȚI DIN BETON ARMAT DISIPATORI DE ENERGIE

(Rezumat)

Se evidențiază tipurile de pereți şlițați disipatori de energie, din beton armat, monoliți sau prefabricați, care au fost propuşi de cercetători, precum şi comportarea la acțiuni seismice a acestor tipuri de pereți. Datorită soluțiilor de disipare a energiei propuse de cercetători pentru pereții structurali din beton armat, ductilitatea de ansamblu a structurii creşte, rezultând un plus de siguranță pentru structură. Obiectivul acestor soluții este de a creea o structură ideală pentru clădirile multietajate înalte, care la acțiuni seismice reduse se comportă rigid dar sub acțiunea unor cutremure de intensitate ridicată se transformă într-o structură flexibilă. Soluțiile de ductilizare a pereților propuse în această lucrare sunt viabile şi uşor de pus în practică. Pentru analiza pereților şlițați cercetătorii au folosit o serie de metode analitice de calcul, printre cele mai importante fiind metoda cadrului echivalent şi metoda elementului finit, ambele fiind prezentate în § **3** al lucrării. Cercetătorii au ajuns la concluzia că prin folosirea celor două metode de calcul poate fi simulată foarte exact şi realist comportarea la încărcări dinamice a pereților şlițați din beton armat.