研 究 速 報

UDC 699.841/.842 : 624.04 : 534

Hysteresis Model for the Shear Behavior of R/C Multistory Frame Buildings with Diaphragms Under Seismic Actions (Part 1)
—Principle of Formation—

耐震壁を有する鉄筋コンクリート造多層建物のためのせん断履歴モデル
—その1 基本概念—

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1. Introduction

After the destructive 1988 Spitak Earthquake in Armenia it was necessary to investigate the reasons of extensive collapses particularly of 9-story R/C frame buildings with diaphragms (shear walls). These buildings were designed in accordance with USSR seismic code. However, they were calculated only in elastic stage. Therefore, to know the reserves of strength and the degree of their ability to resist that earthquake it is necessary to make nonlinear seismic response analyses.

Preliminary analyses of these buildings using the Spitak earthquake accelerogram recorded at Gukasian was carried out by T. Ugata and T. Okada [1]. It was assumed that joints were connected rigidly and precast panels of exterior walls did not contribute to the stiffness of frame. The building was analyzed in the longitudinal direction. The authors note that "the calculated fundamental period was much longer than observed one···, because the stiffness of wall panels and the contribution of reinforcement to the stiffness of members were not considered in the analysis. The response acceleration was, therefore, relatively small···. If these contributions were considered, the natural periods would be shorter and the response acceleration could be expected much larger. Further analyses considering these contributions should be carried out."

Besides, it is much of interest the earthquake response analyses in the diaphragms (transverse) direction of these buildings. This calculation was not carried out in [1] because, apparently, the authors did not have the enough data of this type diaphragm hysteresis deformation regularity. During calculation there were used Origin-oriented and Degrading trilinear hysteresis models.

It should be noted that long before the Spitak earthquake, analytical investigations of R/C frame buildings erected in Armenia were carried out by E.E. Khachian [2]. That were different versions of nonlinear response calculation carried out in the Soviet Union for the first time using 4 accelerogram records: Ferndale, Hollister, Eureka, Taft. The author used bilinear elasto-plastic and with hardening hysteresis models. That investigations were the important step in the development of earthquake engineering in the USSR but gave first of all only qualitative results because accepted hysteresis models did not reflect the real behavior of R/C buildings members.

As it is noticed in S. Otani's paper [3] bilinear hysteresis models are acceptable mainly to describe the flexural behavior of ductile R/C structures. The same is noticed about Ramberg-Osgood, Clough, Takeda and Degrading trilinear hysteresis models, which were discussed in this paper.

Using above mentioned and other known hysteresis models or their modifications and combinations for nonlinear analyses of 9-story buildings, apparently, will not allow to get correct results because these buildings erected in Armenia with diaphragms in which shear deformations are predominate. Of course, for some constructions depend on diaphragm sides ratio, height of buildings, stiffness of slabs and other factors predominate deformation in diaphragm might become bend. For instance, based on results of full-

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scale 7-story R/C building tests, as a part of U.S.-Japan Cooperative Research Program [4], T. Kabeyasawa, S. Otani and H. Aoyama [5, 6] in their investigations noticed that flexural deformations are predominated in diaphragms of buildings with more than 5 story height. But, comparing this 7-story building with 9-story erected in Armenia, it might be said that column sections are 50×50cm and 40×40cm respectively and for almost the same spans and height of floors thickness of shear walls are 20cm and 14cm respectively. From the other side, thickness of slabs are 12cm and 22cm respectively. Consequently, stiffness of slabs in 7-story building relatively the stiffness of vertical members is significantly smaller than in 9-story. As it seemed to me, this is a reason that flexural deformations are predominate in the 7-story building's shear wall. In the 9-story buildings, backwards, stiffness of slabs is much larger than stiffness of vertical members and therefore during vibration, as it noticed in [2], slabs move in horizontal directions without turn in vertical direction. That is why shear deformations are predominated in 9-story building's diaphragms.

Hence, for nonlinear earthquake response analyses of 9-story R/C frame buildings it is necessary to develop a hysteresis model which will take in account the predominance of shear deformations reflecting the actual behavior of diaphragm realistically.

2. Principle of Hysteresis Model Formation

The extensive experimental data which were obtained by the author's tests on different shear walls [7] was used to develop a hysteresis model for R/C constructions with predominance of shear deformations. The experimental horizontal force-displacement relationships analysis showed that there are some regularities existing in shear walls deformation process under reversal loading [7]. For example, Fig. 1a characterizes the behavior until destruction of one story one span diaphragm which geometrical sizes and reinforcement are correspond to those in typical design of 9-story frame building (series 111). From here it is obvious that with the horizontal load increasing on each stage the angle between the loading curves and horizontal axis from cycle to cycle decreases. It means the continuous downfall of stiffness. As a whole, the hysteresis loops shape for this construction is determined by "rigid" type of nonlinearity at loading. On each stage the loading curves are striven for the point corresponding to the previous maximum value of displacement. Unloading curves from cycle to cycle at first are parallel to each other but with bringing near to the horizontal axis the angle of their inclination decreases with the increasing of stress-strain stage. The envelop curve as it is obvious from the graph can be represented as four linear broken line. It is necessary to say that for the present not enough experimental data accumulated about descending limb of the envelop curve and for its clarification further investigations should be carried out.

To explain the principle of supposed model formation there are schemes brought on Fig. 2. When the force and displacement exceed the values respectively FC and DC which are represent the coordinates of the cracking point nonlinear behavior of construction will begin. At that time in structure the crack will occur with length L_1 which is correspond to the displacement DD_1. Let us assume that unloading happen after this moment. As experiments show until the FC level unloading line may be taken parallel to envelop curve's initial stiffness line. Then the direction of unloading line change to the point with coordinates -FC,-DC. When unloading line cross the horizontal axis (force is equal zero) crossing point with coordinates O, DR^+ characterize the residual deformation of structure. In this moment crack has the same length but does not close and width of its opening is reduce. Completely crack will close when structure is loading in the opposite direction and loading line reaches the vertical axis (horizontal displacement is equal zero). Then with the increasing of horizontal force take place the squeezing of this crack and new crack occur in the direction perpendicular to first. Here the displacement DD_2 is bigger than -DC. It should be noted that at the symmetrical loading in opposite directions envelop curves of each direction for this structure have the same absolute value of cracking, yielding and ultimate points. Let us assume now that unloading begins at the displacement DD_2. Repeating above mentioned reasoning, when the horizontal force is equal zero the structure

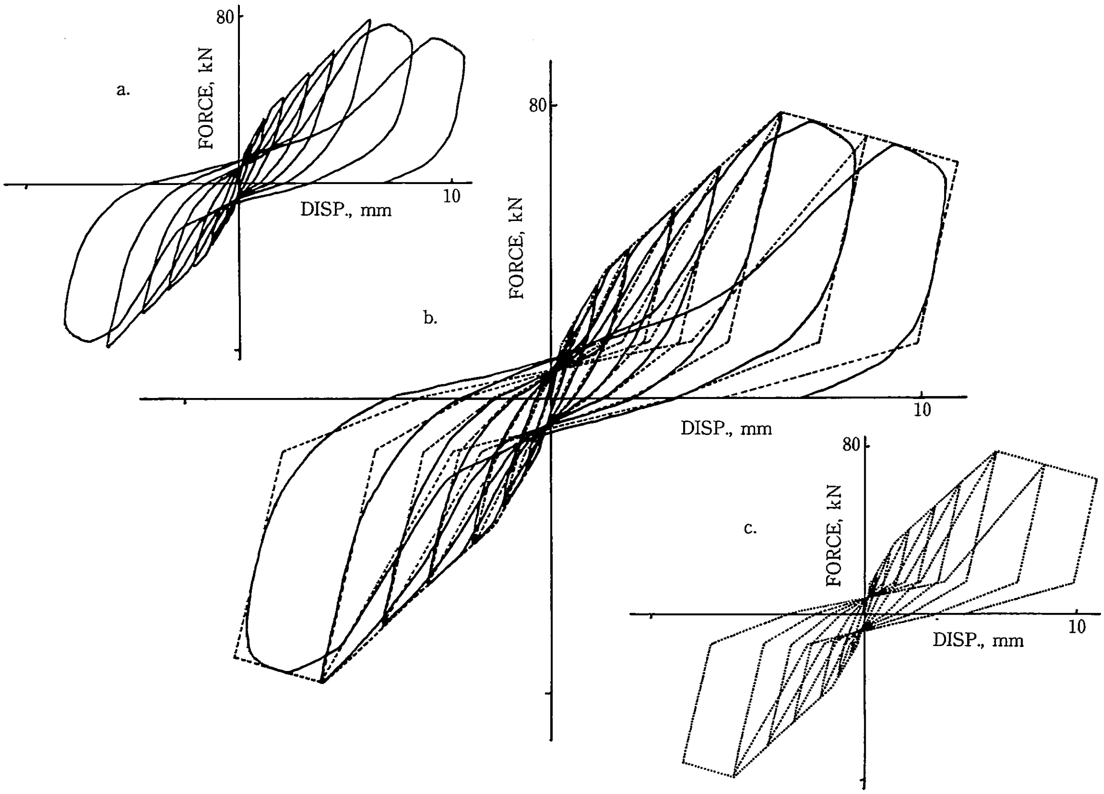

Fig. 1 Comparison of experimental hysteresis loops and model

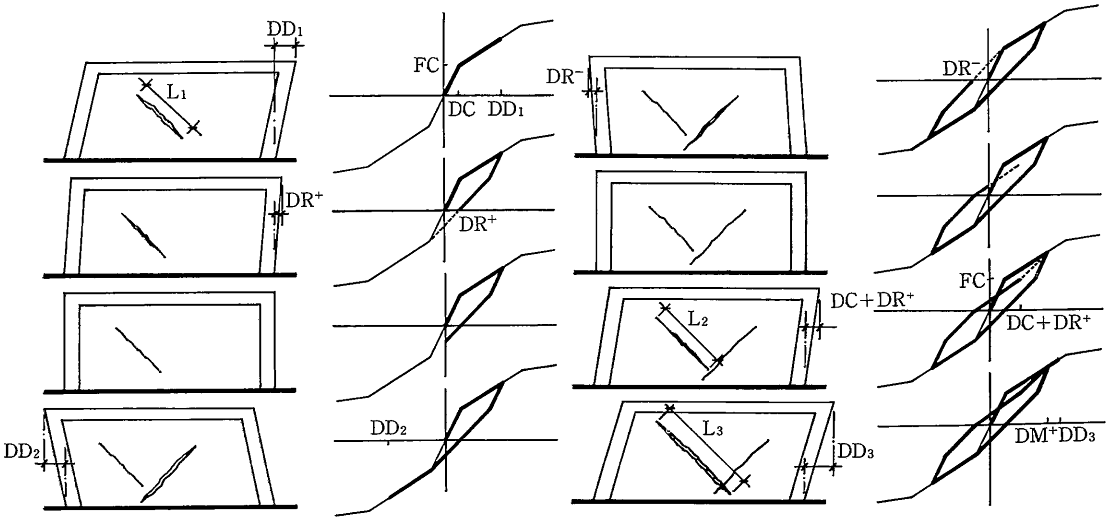

Fig. 2 Schemes to explain the principle of hysteresis model formation

will have residual deformation DR^- and after that new loading cycle will begin. The crack which occurred at first cycle is start to relax and that makes the reduction of loading stiffness in comparison with initial stiffness. Therefore loading line strives for the point with coordinates FC, $DC+DR^+$ which is considering as new cracking point. When the loading line cross the vertical axis the mentioned crack begin to open and at the displacement $DC+DR^+$ increasing of crack width and length to the value L_2 simultaneously occur. It means that new parts of wall body adjoining with the crack and other undamaged parts are involved in the work under horizontal force. As a result the stiffness is increases and the loading line changes its direction to the point corresponding maximum displacement DM^+ of previous cycle. Then loading line is passes along the envelop curve up to the displacement DD_3 where again unloading begins and so on. In the interval between displacements $DC+DR^+$ and DD_3 continuously occur increasing of crack width and length to the value L_3.

With the load increasing new cracks appear which cross each other and cover as net whole diaphragm body. It is assumed that the described deformation process takes place up to the construction collapse. Following this principle hysteresis model was formatted (Fig. 1c), the initial data corresponding the graph shown on Fig. 1a were used. For clarity both graphs are combined and shown on Fig. 1b. From this it obvious that proposed model is close enough to describe the shear behavior of diaphragm at horizontal loading.

3. Concluding remarks

The principle of hysteresis model formation is proposed to describe the shear behavior of R/C structures. The hysteresis model was developed on the basis of experimental results obtained during horizontal load reversals tests of different type of diaphragms (shear walls). Using that principle the hysteresis model was formatted for diaphragms of 9-story r/c buildings which had extensive damages at 1988 Spitak earthquake in Armenia. The comparison of the hysteresis model and experimental hysteresis loops gives the reasonable matching and the model is acceptable in the further analysis.

Acknowledgment

The author deeply appreciates to Professor T. Okada for creation the opportunity to guiding research work in his laboratory and for valuable remarks at the hysteresis model development. The author would like to express his gratitude to Lecturer Y. Nakano, Research Associate F. Kumazawa and Graduate student T. Inoue for active participation and remarks at discussion the model.

(Manuscript received, September 27, 1990)

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