LEARNING FROM THE WENCHUAN EARTHQUAKE: KEY PROBLEMS IN COLLAPSE ANALYSIS OF STRUCTURES

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ABSTRACT:

Up to now the Wenchuan Earthquake has caused nearly 70,000 casualties. It is widely believed that over 95% of the casualties and injuries were due to collapses of millions of buildings. Then one question is why there are still so many collapses after many years aiming to ensure “no collapse under big earthquake” which was first brought forward in 1989 Code for Seismic Design of Buildings (GBJ11-89, China). In fact how to resist collapse have received increasing attention in structural engineering communities for several decades, especially after the 9.11 terrorist attack on the twin towers in New York city. After the 5.12 Wenchuan Earthquake, the authors joined a damage investigation organized by the National Key Basic Research and Development Program of China (973 Program) in the disaster area, especially at Dujiangyan, Hongbaizhen, Beichuan and Yingxiu. Based on the survey around the heavily damaged area, three key problems in collapse analysis of structures were identified as description of discontinuous displacements, collision/impact between structural elements and adjacent buildings, and geometric nonlinearity of structures. Some of the typical collapses in the Wenchuan Earthquake are provided. Solution of the key problems in framed structures and thus numerical simulation of collapses were given in brief. Some research work trying to solve the solutions is also introduced.

KEYWORDS: Wenchuan Earthquake, Collapse analysis, Discontinuous displacement, Collision/Impact, Geometric nonlinearity

1. INTRODUCTION

About thirty years after the Tangshan Earthquake, the 5.12 Wenchuan Earthquake shocked the world again with nearly 70,000 casualties and more than 15,000 still missing. It has been proved by damage investigations into many devastating earthquakes that the genesis great property losses and casualties are structural collapses. As a matter of fact many efforts have been focused on finding ways to prevent progressive collapse of structures. After the 9.11 terrorist attack on WTC in New York, DOD (Department of Defense) and NIST (National Institute of Standards and Technology) of USA issued a series of design guidelines and standards [1-3]. In AASHTO (American Association of State Highway and Transportation Officials) LRFD bridge design specifications the forth limit state of extreme event is brought forward to consider structural safety under extreme conditions such as strong earthquake. In Europe an international cooperation program (COST C26 ACTION) was started in 2006 in order to ensure structural safety under catastrophic events [4]. The current object, however, is to promote understanding over structural performance in extreme conditions.

In China, “no collapse under big earthquake” has been established as an object of structural design ever since the Tangshan Earthquake in 1976. It was first stated in the 1989 Code for Seismic Design of Buildings (GBJ11-89) and then in the 2001 Code for Seismic Design of Buildings (GB500011-2001). As early as in 1991 it was first proposed in the development strategy of structural engineering by National Science Foundation of China (NSFC) to study the structural performance under catastrophic events [5]. In 2006 the Ministry of Science and Technology (MOST) released a national support program, one topic of which was about “Researches on technologies in fighting calamity to key structures in cities”. Another key research plan on “Dynamic Catastrophe of Key Structures” was released by NSFC in 2007.

It seems that more and more attention has been focused on structural safety. The achievements, however, are far from satisfactory. It was estimated that more than one million buildings collapsed in the Wenchuan Earthquake. One of the most frequently asked questions is that why there are still so many collapses of buildings. The main reason is that there is no practical collapse analysis and thus no tools to measure what exactly happens during structural collapses. Therefore the design guidelines and research efforts are more qualitative than quantitative. The design measures to counteract progressive collapse depend more on conceptual detailing rather than analysis and calculation. The authors and their group have been studying structural collapse for many years. Several problems in collapse analysis of framed structures have been brought forward [6]. After the 5.12 earthquake, the authors joined a damage investigation in the disaster area, especially at Dujiangyan, Beichuan, Yingxiu and Hongbaizhen, which was organized by the National Key Basic Research and Development Program of China (973 Program). Based on the investigation and current research work, the authors believe that it's time to perform quantitative analysis of structural collapses with more elaborate model. In this paper three key problems in collapse analysis and their (possible) solutions are presented.

2. DISCONTINUOUS DISPLACEMENT

An intact structure under extreme conditions usually will subject to various failures such as cracking, yielding and even fracture. As far as the distribution of displacement and deformation is concerned, it may be termed as having discontinuous displacement. A typical example is the failure of a beam-column member in the formation of a plastic hinge – the slope along the member has some discontinuities, which has been widely studied over the past decades.

One of the key problems in collapse analysis of structures is to model rationally the displacement discontinuities in structural elements, such as translation and rotation discontinuities due to member failure, which eventually may cause fragmentation and trigger progressive collapse. The so-called Discrete Element Method (DEM) [7, 8] has been used to model translation displacement discontinuities (see for example [9]). However, the effectiveness of such methods in collapse analysis is limited by the tremendous computational efforts required as well as the difficulties in determining appropriately material properties for special components such as spring or contact elements.

2.1 Discontinuous Displacement in Beam-column Members

These displacement discontinuities are most common in damage investigation as shown in Fig.1 and Fig.2, where some failures with discontinuities in slope (for example, Fig.1) can be successfully described by plastic hinge model. There are plenty of literatures on using plastic hinges in collapse analysis and seismic assessment such as [10-12].


(a) (b)

Figure 1 Typical failure as plastic hinge(s): (a) top of one column; (b) ends of a row of columns

(a) (b) (c)

Figure 2 Member failures beyond plastic hinge: (a) shear failure; (b) axial crushing; and (c) disconnection

However plastic hinge model is incapable of describing the discontinuous displacements associated with shear failure and axial crushing (see Fig.2a and Fig.2b), i.e. the transverse and longitudinal displacements, as well as those in disconnection between members (see Fig.2c).

(a) (b)

Figure 3 Displaced columns leading to settlement of a building at Dujiangyan: (a) big view; (b) close look

In practice these three components of discontinuous displacement (i.e., rotation, transverse and longitudinal displacements) are usually combined together. Sometimes the additional longitudinal displacement activated by axial crushing may cause progressive failures due force re-distribution even under gravity load. For one building at Dujiangyan (see Fig.3), for example, the two columns at the first floor are seriously displaced so that the corner of the building had significant settlement. It will probably collapse under strong aftershock.

It is obvious that plastic hinge model is far from enough to describe the displacement discontinuities in beam-column members and thus not sufficient for collapse simulation of structures such as those shown in Fig.4. Based on singularity functions, mixed hinge model was proposed by the authors to depict three displacement discontinuities (i.e., rotational, transverse and longitudinal) in plane beam-column members. The discontinuities are assumed to be concentrated at member ends. The member modelled with mixed hinges is consistent with traditional member models and thus make the programming very convenient. It can also have different combination of discontinuous displacements, such as rotational & transverse or rotational & longitudinal, to model the evolution of member failures. For more details the readers are referred to [13].


(a) (b)

Figure 4 collapses of structures: (a) partially of an office building at Dujiangyan; (b) completely of one school building at Yingxiu (Adjacent building were heavily damaged)

The research work to extend the mixed hinge model to 3D beam-column members is undergoing in the authors' research group, which will be reported lately.

2.2 Discontinuous Displacement in Slab/Wall Elements

It is well known that most of the casualties are caused by collapses in strong earthquakes. In fact it might more appropriate to say that most of the casualties resulted from collapse of floor slabs and walls. Examples are given in Fig.5. More pictures can be found in public sources.


(a) (b) (c)

Figure 5 (a) pre-cast and cast-in-place slabs hanging; (b) in-fill wall collapsed; (c) inclined in-fill walls

Unfortunately such kind of behavior of slab/wall under extreme conditions cannot be simulated appropriately using available models. The application of DEM and its extended form is also prohibited by similar problems in dealing with beam-column members as described in Section 2. In current design codes, the roles that slab/wall plays in the whole structural system carrying external loads is usually simplified in modeling. This will cause some deviation between the design and the reality, which might be much greater in plastic stage. With development of high performance computer, it's probably the right time to establish models of slabs and walls in structural analysis, especially in collapse analysis under extreme conditions. Otherwise it may lead to misunderstanding of structural performance and thus wrong decision in dealing with catastrophic events.

In the authors' research group, research work on modeling slab/wall in extreme cases was started immediately when the authors came back from the disaster area, which will be reported lately.

3. COLLISION/IMPACT

Collision/impact is common phenomenon in earthquakes, such as during the 1989 Loma Prieta Earthquake [14]. Although it is hard to observe collisions during structural collapses in catastrophic events, they can still be traced in some seriously damaged buildings. Collision/impact may trigger dynamic force re-distribution and hence progressive collapse. It is believed that impact is the main reason leading to the collapse of WTC in the 9.11 terrorist attack. In Fig.6, the second floor of one building still under construction at Yingxiu vanished during the Wenchuan Earthquake. When the upper floors fell down on the slab of the first floor, one span was punched through (Fig.6b) and one was heavily damaged (Fig.6c). In another building, the in-fill wall fell down onto the stairs slab causing it crashed. Obviously they may cause serious consequences.


(a) (b) (c)

Figure 6 Damaged building at Yingxiu: (a) one storey vanished; (b) slab punched through; (c) slab damaged

There are some literatures on collision analysis in structural engineering, which, however, are mainly focused on pounding between adjacent buildings ([15], for example). The solutions were usually trying to obtain contact forces for the following calculations, where the dynamic effects such as velocity re-distribution due to impact are neglected. More recently some attention has been put on the collision between structural members during collapse ([16], for instance) to take into account the velocity re-distribution. However, the assumption to assume the bodies involved in impact as rigid, which is usually adopted in analysing impact between vehicles and barriers, might be inappropriate since the impact between rigid and deformable bodies are quite different.

A collision model based on velocity restraint conditions was presented by the authors and successfully applied in pounding analysis of adjacent buildings [17]. By employing a Lagrangian multiplier to modify kinetic energy, the restraint condition imposed by collision is incorporated into the equations of motion, which will lead to the equilibrium equation of impulse after integration over time interval. They can be solved in a unified form with the traditional equation of motion. It is not necessary to obtain the contact forces in advance, which, if required, can be obtained directly through force equilibrium condition at nodes. For details the readers are referred to [18].

4. GEOMETRIC NONLINEARITY

It is obvious that in structural collapses there must be large displacement and large deformation, which is generally the main topic of geometric nonlinearity. There are tremendous amount of literatures dealing with geometric nonlinearity. Based on the choice of referring coordinates, methods regarding geometric formulation of deformable bodies may be categorized into two types: Lagrangian Formulation and Eulerian Formulation. In 1979 Argyris and Doltsinis employed the current unstressed configuration to deal with large deformation and inelastic problems, where iteration is needed since the current configuration remains unknown [19]. In structural analysis the geometric nonlinearity related with large deformation is usually avoided by assuming concentrated plasticity of materials. Thus in general only large displacement/large rotation with small deformation is considered in structural analysis.

4.1 Large Displacement/Large Rotation

Some simplified methods were developed to consider the geometric non-linearity of framed structures, usually known as $P-\Delta$ effects. By introducing a geometric stiffness matrix, the coupling between bending moment and axial force can be taken into account in terms of the effective stiffness. These methods, however, may be not suitable for collapse analysis of framed structures. For example, the variation of axial forces cannot be considered appropriately in dynamic analysis.

To consider large displacement/large rotation in collapse analysis of frame structures, the authors adopted the current unstressed configuration by which the variation of axial forces is no longer a problem. The configuration is formed by an imaginary removal of stresses as well as the elastic part of local deformation from the deformed configuration after fixing local coordinates on the current unstressed configuration. The remaining inelastic deformation is responsible for the transformation of the unstressed configuration from the initial to the current state. Using the step-by-step method, the displacement increments for each step may be assumed to be very small, so that the assumption of small displacement can be adopted and then the referring configuration will change continuously. Thus it may be called accumulated large displacement with small deformation. This scheme has been successfully applied in numerical examples in [13, 18].

For slab/wall elements, special techniques are probably necessary considering large displacement/large rotation.

4.2 Failure due to Buckling

In collapse analysis another problem related with geometric nonlinearity is buckling. In practice, however, buckling analysis of structures under dynamic load such as ground shaking is not well established. There have been structural collapses reportedly resulted from buckling of one or several members of the structure. So failure due to buckling must be included in collapse analysis.

The authors have used the current unstressed configuration to study the failure of a braced portal frame, which shows that buckling of the bracing member in compression can be well traced with its residual load-carrying capacity still working. The well-known three-hinged buckling problem can also be solved using the current unstressed configuration. Referring to the current unstressed configuration might be a good choice considering buckling failure in a consistent manner with other geometric nonlinearity.

5. NUMERICAL EXAMPLE OF COLLAPSES OF A FRAMED STRUCTURE

The aforementioned three problems have been solved for 2D framed structures. Here one example to simulate the collapse of a framed structure with one soft story is given. The input earthquake record is taken from the 1976 Ninghe earthquake, which is measured as M6.9 and considered as a strong after shock of the Tangshan Earthquake. Sketches of the structure are shown in Fig.7 and the input earthquake record is shown in Fig.8. The peak ground acceleration (PGA) is 145.8gal.

Collapse of the frame in pan-cake is sketched in Fig. 9 and one of the real collapses is shown in Fig.4b. The collapse with weak foot is sketched in Fig.10, which are quite common in the Wenchuan Earthquake. Finally the collapse of the structure with a weak second story is shown in Fig.11 with the example building shown in Fig.6a. It is obvious that the solutions provided by the authors are able to simulate the collapses of 2D framed structures.

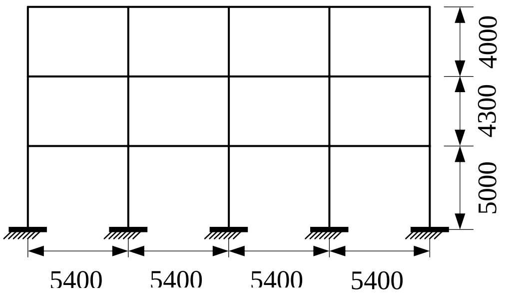

Figure 7 Sketch of frame (unit mm)

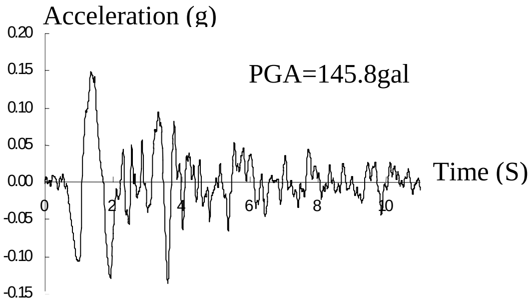

Figure 8 Ground motion record

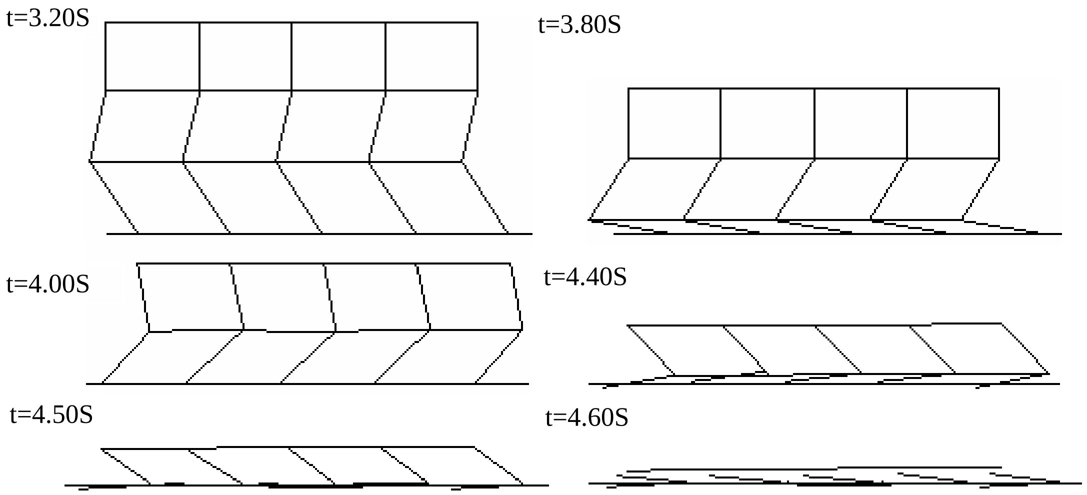

Figure 9 Collapse in pan-cake

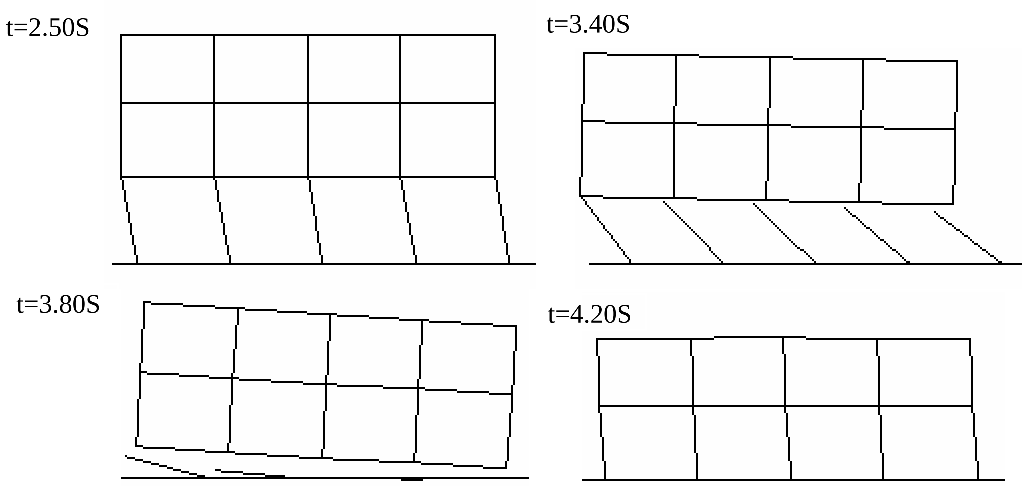

Figure 10 Collapse with weak ground story

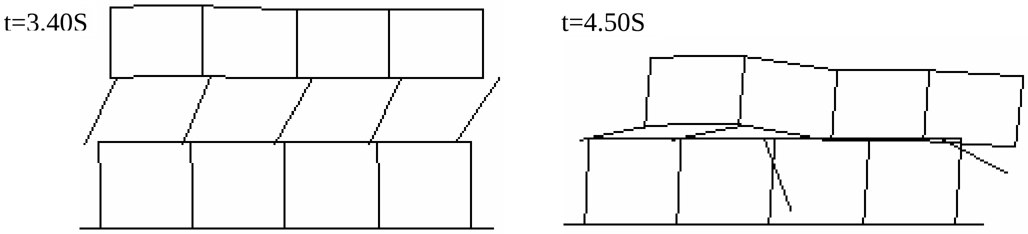

Figure 11 Collapse with a weak second story

6. CONCLUSIONS

Base on a damage investigation over the disaster area of the Wenchuan Earthquake, three key problems in collapse analysis are brought forward as description of discontinuous displacements, collision/impact and geometric nonlinearity of structures. The solutions for framed structures are also given based on the research work carried out by the authors' group. The numerical examples show that the real collapse process could be appropriately simulated. Some possible solutions in dealing with special problems are also provided.

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REFERECES

[1] Department of Defense (DOD). (2001). Interim antiterrorism/force protection construction standards - progressive collapse design guidance.
[2] National Institute of Standards and Technology (NIST). (2002). Standards, technology, and practices for: cost-effective safety and security of buildings and critical facilities.
[3] Department of Defense (DOD). (2005). Design of buildings to resist progressive collapse. UFC 4-023-03.
[4] Federico M. Mazzolani. (2007). Urban habitat constructions under catastrophic events: the COST C26 Action. Proceedings of the first International Workshop on Performance, Protection and Strengthening of Structures under Extreme Loading (CD-ROM), Whistler, Canada, August 2007.
[5] Liu, X.L. (1996). The status and prospects of structural engineering. People's Jiaotong Press, China
[6] Zhang, L.M. and Liu, X.L. (2001). Some issues in the collapse analysis of frame structures. *Journal of Shanghai Jiaotong University*, 35 (10): 1578-1582 (in Chinese)
[7] Goodman, R.E., Taylor, R.L. and Brekke T. (1968). A Model for Mechanics of Jointed Rock. *Journal of Soil Mechanics & Foundation Division, ASCE*, 94(3): 637-660
[8] Cundall, P.A. (1971). A Computer Model for Simulating Progressive, Large-Scale Movement in Blocky Rock System. in International Symposium on Rock Fracture, Nancy, France. 129-136
[9] Hakuno, M. and Meguro K. (1993). Simulation of Concrete-Frame Collapse due to Dynamic Loading. *Journal of Engineering Mechanics, ASCE*, 119(9): 1709-1723
[10] Park, Y.J. and Ang, A.H.-S. (1985). Mechanical Seismic Damage Model for Reinforced Concrete. *Journal of Structural Engineering, ASCE*, 111(4): 722-739
[11] Kunnath, S.K., Reinhorn, A.M. and Abel, J.F. (1991). A Computational Tool for Evaluation of Seismic Performance of Reinforced Concrete Buildings. *Computers & Structures*, 41(1): 157-173
[12] Kaewkulchai, G. and Williamson, E.B. (2004). Beam Element Formulation and Solution Procedure for Dynamic Progressive Collapse Analysis. *Computers & Structures*, 82: 639-651
[13] Zhang, L.M. and Liu, X.L., et al. Mixed hinge model for displacement discontinuities in beam-column members Part I: theory (submitted).
[14] Kasai, K. and Maison, B.F. (1997). Building pounding damage during the 1989 Loma Prieta earthquake. *Engineering structures*, 19(3): 195-207
[15] Papadrakakis, M., and Mouzakis, H., et al. (1991). A Lagrangian multiplier solution method for pounding of buildings during earthquakes. *Earthquake Engineering and Structural Dynamics*, 20: 981-998
[16] Kaewkulchai, G. and Williamson, E.B. (2006). Modeling the impact of failed members for progressive collapse analysis of frame structures. *Journal of Performance of Constructed Facilities, ASCE*, 20(4): 375-383
[17] Zhang, L.M. and Liu, X.L. (2004). Analysis of pounding between adjacent structures. *Journal of Shanghai Jiaotong University*, 38(6): 941-946 (in Chinese)
[18] Zhang, L.M. and Liu, X.L., et al. Modeling collisions in structural analysis by imposing restraint condition on velocity. (ready to submit).
[19] Argyris, J.H., and Doltsinis, J.St. (1979). On the large strain inelastic analysis in natural formulation, Part I: quasistatic problems. *Comp. Meth. Appl. Mech. Engrg.*, 20: 213-252