Analysis of the Collapse Behavior of Reinforced Concrete Frame under Seismic Excitation

Ren-Zuo Wang[1], Keh-Chyuan Tsai[2]

1.Associate Research Fellow, National Center for Research on Earthquake Engineering, Taipei, 106, Taiwan.
Email: rzwang@ncree.org.tw

2.Director of NCREE, Professor of Civil Engineering, Dept of Civil Engineering, National Taiwan University, Taipei, 106, Taiwan.
Email: kctsai@ncree.org

Abstract

In this paper, the explicit vector form intrinsic finite element (VFIFE, V-5) method is used to analyze the collapse of a reinforced concrete (RC) frame under seismic excitation. In view of the preceding research purpose, four major sets of research questions to be addressed in this study are as follows: (1) The structure systems Model for mass points of the VFIFE method, (2) The motion behavior of space structure with large deformation and rotation from continuous states to discontinuous states can be analyzed by the VFIFE method, (3) The progressive failure of the structure components was investigated in detail by considering the material nonlinearity and associated failure criteria of the modified Park & Ang damage index into the cracking analysis of the elements, (4) In order to simulate the progressive collapse behavior of the structure, therefore we need to provide for the mechanisms of contact detection algorithm and calculate with contact force among these frame elements.

Keywords: VFIFE, damage index, progressive collapse, contact detection, contact force.

1. INTRODUCTION

To prevent the immeasurable losses of human lives and social properties due to earthquakes and terrorist attacks, it resistance evaluation and retrofitting of civil infrastructures becomes an important issue of many countries in the world. Great attention has been focused on a type of failure known as progressive collapse since the Ronan Point apartment collapse in London in 1986 (Griffiths et al. 1986). In recent year, however, terrorist attacks against the Alfred P. Murrah Building in Oklahoma City in 1995, and the World Trade Center could not withstand the fires from terrorist attacks that induce progressive collapse of structures at the New York in 2001. The 27 May 2006 earthquake hit the Provinces of Yogyakarta and Central Java, and lead to RC and brick building's collapse. Besides experimental and theoretical studies, the numerical simulation is another way to assist engineers to understand the nonlinear dynamic failure behavior of structure under the earthquake excitation. Nonlinear analysis methods developed since last century are used to study the behavior of structures with material and geometrical nonlinearities. Gallagher and Padlog (1963) first introduce the geometrical stiffness matrix into the nonlinear analysis of structure by considering the nonlinear strain terms in the formulation. Argyris et al. (1978) and Elias (1986) have tried to modify the definition of bending moment to derive a modified geometrical stiffness matrix to satisfy the equilibrium requirement at each deformed state. Yang and Kuo (1994) proposed a method to decompose the displacement of structural element into rigid body displacement and natural deformation displacement in each incremental step of the computation and this kind of decomposition can lead the geometrical stiffness matrix pass the rigid body motion test. It is well known that the core idea of the nonlinera analysis of structure is how to clearly identify the rigid body component and the deformation component in the motion.

Recently, A vector form intrinsic finite element (VFIFE, simply called V-5) was proposed by Ting et al. (2004a, 2004b) and Shi et al. (2004). The VFIFE method has been successfully applied to the nonlinear motion analysis of 2D frame (Wu et al. 2006) and the dynamic stability analysis of space truss structure (Wang et al. 2005a, 2005b, Wang et al. 2006). Due to the characters of the VFIFE method, it is very easy to be applied to study the highly nonlinear dynamic behavior of a structure system from continuous to discontinuous states. In this paper, the theory of space frame element in VFIFE is briefly introduced, and describes RC frame in VFIFE Method. Besides, analysis of collapse structures is included multiple space frame elements motion for large deformation and rotation from continuous states to discontinuous states. It is clear that we need to consider the contact conditions for two frame and contact with the frame between ground in space frame.

2. FUNDAMENTALS OF THE 3D FRAME IN VEFIFE

A new computational method so called the Vector Form Intrinsic Finite Element is developed by Ting et al. (2004 a, b) to handle engineering problems with the following characters: (1) containing multiple deformable bodies and mutual interactions, (2) material non-linearity and discontinuity, (3) large deformation and arbitrary rigid body motions of deformable body. Since the conventional FEM based on variational method requires the total virtual work to be zero but does not require the balance of forces at nodes. These unbalanced residual forces will do some non-zero work under virtual rigid body motion and cause the inaccuracy and un-convergence of the calculation results. The computation procedure and some concepts of this VFIFE method are similar to the FEM. But the major difference is that the VFIFE does not apply the variational principle on the stress expressed equilibrium equations in its formulation. Instead, VFIFE maintains the intrinsic nature of the finite element method and makes strong form of equilibrium at nodes, the connections of members.

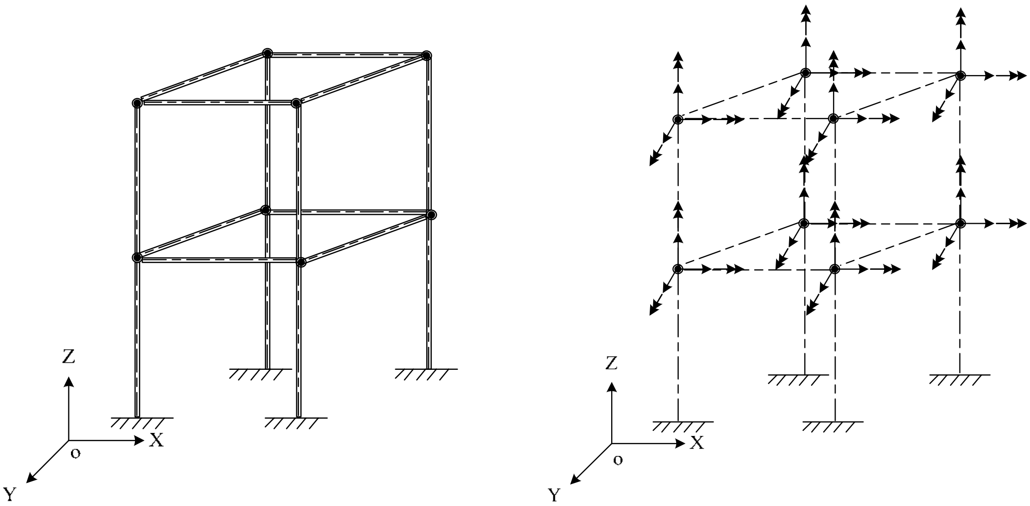


Figure 1 (a) A space frame structure, (b) Discrete particles modeling of space frame structure system by the VFIFE method.

In other words, the continuous bodies are represented by a set of mass point as shown in Fig. 1. and using lumped mass techniques. Every mass points is satisfied New's second law and physical significance which is interpretable. The following statement discuss with a space frame element that the theory of VFIFE is presented to study the motion behavior of a space structure with large deformation under seismic excitation. Similar to other well-developed VFIFE elements, a convected material frame and explicit time integration for the solution procedures are also adopted. The description of kinematics to discrete rigid body and deformation displacements, and a set of deformation coordinate for each time increment to describe deformation and internal nodal forces are described.

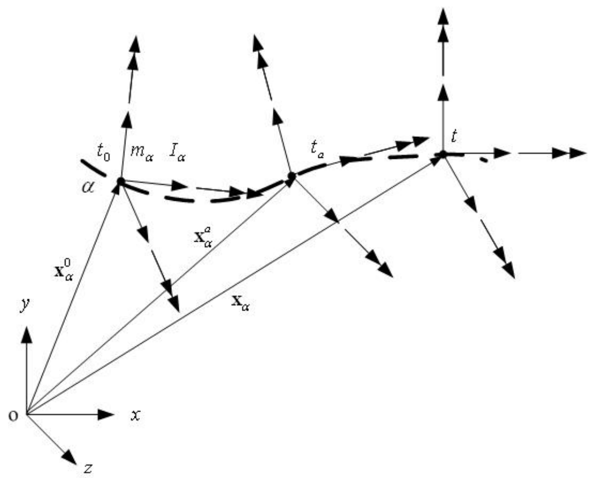


Figure 2 Motion trajectory of a particle α of frame structure with 6 degree of freedoms in space

The basic modeling assumptions for the VFIFE method for 3D frame structures are essentially the same as those in classical structural analysis. A frame is constructed by means of prismatic members and joints. Members are subjected to forces and moments as shown in Fig. 2. Joints have work equivalent masses and mass moment of inertias, and can be modeled as discrete rigid bodies. Motions of the joints can be described by the principles of virtual work or equations of motion for particles. Members have no mass, and are thus in static equilibrium. The corresponding internal forces $\hat{\mathbf{f}}^* = (\hat{f}_{2x}, \hat{m}_{1y}, \hat{m}_{1z}, \hat{m}_{2x}, \hat{m}_{2y}, \hat{m}_{2z})^T$ of the frame element in the deformation coordinate system can be derived by the principle of virtual work. From the static equilibrium equations, all the internal forces at the two nodes of the frame element can be calculated. All the internal forces at those two nodes of a frame element in the deformation coordinate system at time t are expressed by a vector $\hat{\mathbf{f}}^{\text{int}}$ as

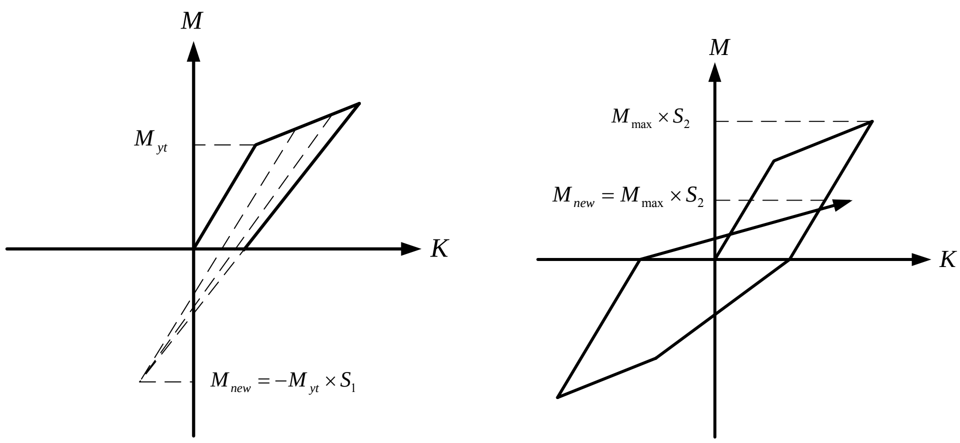
$$\hat{\mathbf{f}}^{\text{int}} = \{\hat{f}_{1x}, \hat{f}_{1y}, \hat{f}_{1z}, \hat{m}_{1x}, \hat{m}_{1y}, \hat{m}_{1z}, \hat{f}_{2x}, \hat{f}_{2y}, \hat{f}_{2z}, \hat{m}_{2x}, \hat{m}_{2y}, \hat{m}_{2z}\} \tag{1}$$

Since all the calculation is within the global coordinates, the internal forces $\hat{\mathbf{f}}^{\text{int}}$ obtained in the local deformation coordinates of each frame element have to be transformed to $\mathbf{f}^{\text{int}}$.

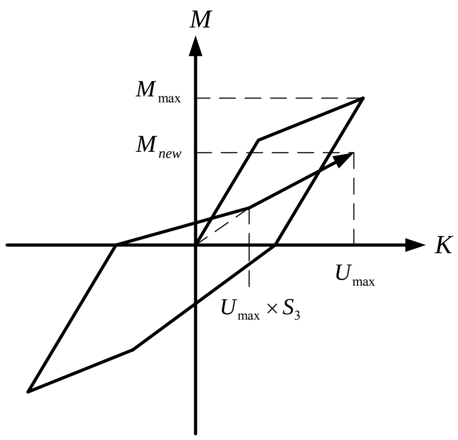
After calculating all the internal forces of element nodes, one can sum over all internal forces $-\mathbf{F}_\beta^{\text{int}}$ and external forces $\mathbf{F}_\beta^{ext}$ applied on a rigid body particle β and obtain the following equation of motion without damping effect:

$$\mathbf{M}_\beta \ddot{\mathbf{d}}_\beta = \mathbf{F}_\beta^{ext} - \mathbf{F}_\beta^{\text{int}} \tag{2}$$

Where $\mathbf{M}_\beta$ is the general mass matrix and $\ddot{\mathbf{d}}_\beta$ is the general displacement vector of the particle β. In the present analysis, the explicit time integration technique is used to solve the Eq. (2). Since the VFIFE method uses the motion and relative displacements of particles to identify the internal forces among them. This feature allows users to do the displacement control type excitation. In the seismic analysis, variations of the displacements and rotations of the element nodes connected to ground can be assigned according to the history of ground motion.



(a) Stiffness Degrading Factor S_1 (b) Strength Deterioration Factor S_2



(c) Pinching Factor S_3

Figure 3 three-parameter model

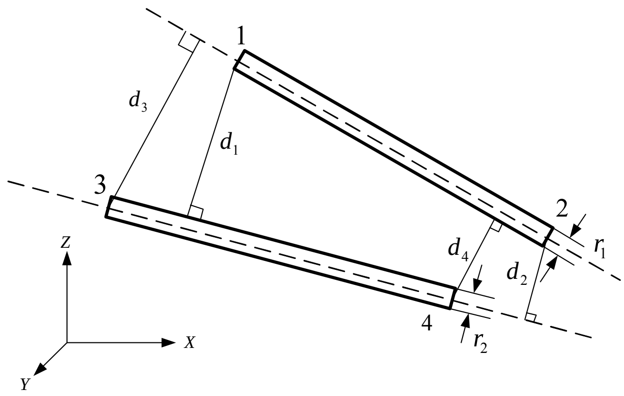


Figure 4 contact detection of 3D frame

3. COLLAPSE BEHAVIOR OF REINFORCED CONCRETE FRAME

In this study, The vector form intrinsic finite element (VFIFE, V-5) method is added to material model for reinforced concrete in space frame and simulate nonlinear dynamic behavior of RC frame. The material model adopted three-parameter model and considered that stiffness degrading(S_1), strength deterioration(S_2), and pinching (S_3) as shown in Fig. 3. A famous and widely used the damage index is that of Park and Ang index (1985). The damage index has implemented in the orginal release of IDARC (Park, Reinhorn and Kunnath, 1987) and moment and curvature are used:

$$D = \frac{K_m - K_y}{K_u - K_y} + \beta_e \frac{\int dE}{M_y K_u} \tag{3}$$

Besides, The VFIFE method is induced modified Park & Ang damage index (Park, Reinhorn and Kunnath, 1987), in order to determine failure criteria of space frames. If the Damage index of reinforced concrete frame arrive at D=0.77, it represent the RC frame elements cracked. The fracture model of space frame is add to mass point and update mass, internal force, external force, point displacement, boundary condition etc. The contact detection conditions of space frame is according to minimum distance method as shown in Fig. 4.

$$gap = d_{\min} - (r_1 + r_2) \tag{4}$$

where

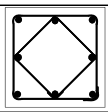
$$d_{\min} = \min\{d_1 \quad d_2 \quad d_3 \quad d_4\} \tag{5}$$

From the Eq. (4), If the gap is smaller than 0, it represent contact. The contact point between two space frame was applied contact force. The preset study provide a method for VFIFE to can consider complete collapse process of reinforced concrete structures.

4. NUMERICAL EXAMPLES

A five floors frame structure is excited by earthquake loading. The frames cross sectional data and material properties are shown in table 1. and maximum compressive stress of concrete is $f_c' = 317.92\ kgf/cm^2$, stiffness degrading $S_1 = 1.2$, strength deterioration $S_2 = 0.98$, and pinching $S_3 = 0.9$. The equivalent loading is obtained by multiplying the acceleration of earthquake. Once the damage index reaching to D=0.77 critical value, the element is fractured. From Fig. 5, one can find that the failure of the structure started from the bottom of the frame. The fractured component moved downward by the gravity force. The contact detection and analysis algorithm have been included in this study.

Table 1. The frames cross sectional data and material properties

	Wide $\times$ Hight	36 cm × 36 cm
Main reinforcement	Steel	8-19φ
	Yielding Stress	5190 kgf/cm^2
Hoop Reinforcement	Steel	6φ@20 cm
	Yielding Stress	6700 kgf/cm^2

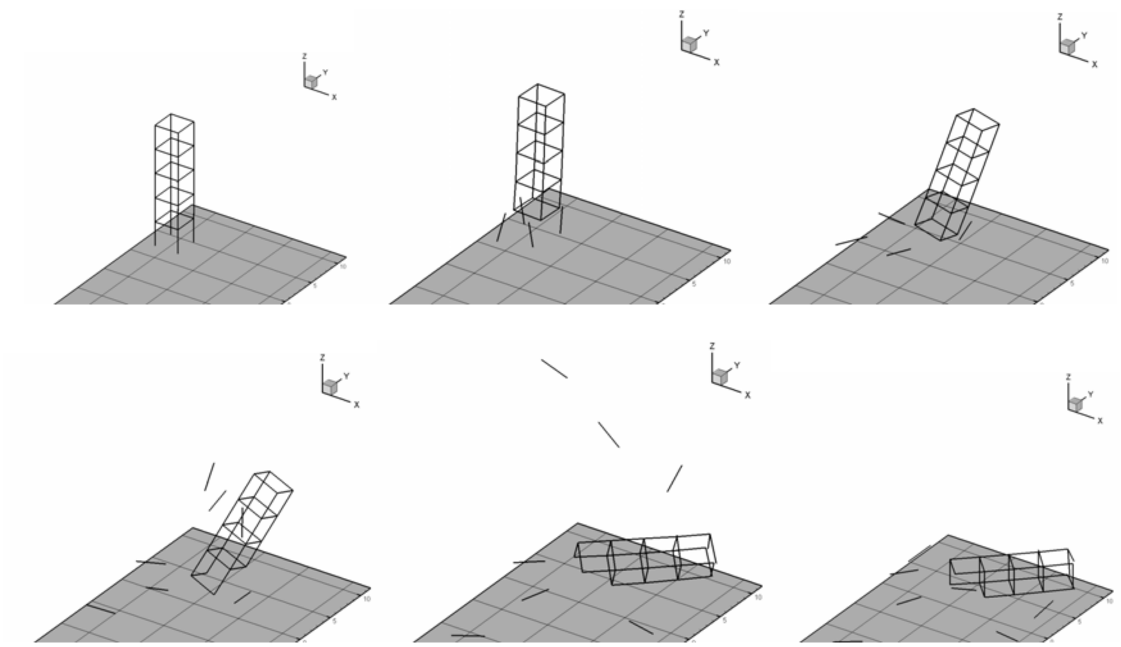


Figure 5 Progressive failure of a space frame structure under seismic excitation.

5. CONCLUSIONS

A novel numerical method called the Vector Form Intrinsic Finite Element (VFIFE) method for the motion analysis of space frame structure is presented. Due to some special features of VFIFE, it can conduct simulations of the progressive failure and collapse of structures relatively easy compared with conventional matrix type structural analysis methods. It is believed that the further development of VFIFE method can provide engineers as an effective and friendly tool to analyze very complicated engineering problems.

6. ACKNOWLEDGEMENTS

The authors are grateful for the help from the National Center for Research on Earthquake Engineering. Especial thanks for Dr. Y. S. Yang, C. L. Wu and Mr. B. Z. Lin for their generous suggestion during this work.

7. REFERENCES

Argyris, J. H., Dunne, P. C., Scharpf, D. W., (1978). “On large displacement-small strain analysis of structures with rotational degree of freedom”, *Computer Methods in Applied Mechanics Engineering*, Vol. 14, pp. 401-451

Elias, Z. M., (1986). *Theory and Methods of Structural Analysis*, John Wiley & Sons, New York, N.Y.

Goldberg, J. E., Richard, R. M., (1963). “Analysis of nonlinear structures”, *Journal of Structural Division, ASCE*, Vol. 89, No.4, pp. 333-351

Griffiths, H., Pugsley, A., Saunders, O. (1986). *Report of the inquiry into the collapse of flats at Ronan Point*, Canning Town, Her Majesty’s Stationary Office. London, England

Park, R., Ang, A. H. S., (1985). “Mechanistic seismic damage model for reinforced concrete buildings”, *Journal of structural Engineering, ASCE*, Vol. 111, No. 4, pp. 740-757

Park, Y. J., Reinhorn, A. M., Kunnath, S. K., (1987). “IDARC:Inelastic damage analysis of RC frame-shear wall structures”, *Technical Report NCEER-87-0008*, National Center for Earthquake Engineering Research, State University of New York, Buffalo NY.

Shih, C., Wang, Y. K., Ting, E. C., (2004). “Fundamentals of a vector form intrinsic finite element: Part III. Convected material frame and examples”, *Journal of Mechanics*, Vol. 20, No.2, pp. 133-143

Ting, E. C., Shih, C., Wang, Y. K., (2004a). “Fundamentals of a vector form intrinsic finite element: Part I. basic procedure and a plane frame element”, *Journal of Mechanics*, Vol. 20, No.2, pp. 113-122

Ting, E. C., Shih, C., Wang, Y. K., (2004b). “Fundamentals of a vector form intrinsic finite element: Part II. plane solid elements,” *Journal of Mechanics*, Vol. 20, No.2, pp. 123-132

Wang, C. Y., Wang, R. Z., Chuang, C. C., Wu, T. Y., (2006). “Nonlinear Dynamic Analysis of Reticulated Space Truss Structure”, *Journal of Mechanics*, Vol. 22, No.3, pp. 235-248

Wang. R. Z., Chuang, C. C., Wu, T. Y., Wang, C. Y., (2005a). “Vector form analysis of space truss structure in large elastic-plastic deformation”, *Journal of the Chinese Institute of Civil & Hydraulic Engineering*, Vol. 17, No.4, pp. 633-646

Wang, R. Z., Kang, L. C., Wu, S. Y., Wang, C. Y., (2005b). “Numerical Simulation of the Whipping Problem of High Pressure Pipe”, *Chinese Society of Structural Engineering*, Vol. 20, No.4, pp. 120-143 (in Chinese).

Wu, T. Y., Wang, R. Z., Wang, C. Y., (2006). “Large deflection analysis of flexible planar frames”, *Journal of the Chinese Institute of Engineers*, Vol. 29, No.4, pp. 593-606

Yang, Y. B., Kuo, S. R., (1994). *Theory & Analysis of Nonlinear Framed Structures*, Prentice-Hall.