STRUCTURAL COLLAPSE ANALYSIS OF FRAMED STRUCTURES UNDER SEISMIC EXCITATION

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ABSTRACT :

This paper presents a numerical procedure which is called the vector form intrinsic finite element (VFIFE, V-5) method. It is used to analyze the nonlinear behavior of structural collapse under seismic excitation. The whole progressive collapse processes of the framed structures in various conditions are also simulated. The numerical procedure in V-5 method provided for new concept to deal with large deformation and rotation from continuous states to discontinuous states. The geometry nonlinear and the nonlinear material have been considered. The damage index of elements is adopted to decide the failure criteria of element joints. In order to simulate the progressive collapse behavior of the structure, the comparison between numerical simulation of V-5 method and shake table experiments demonstrates the accuracy of V-5 method.

KEYWORDS:
vector form intrinsic finite element, progressive collapse, damage index

1. INTRODUCTION

To prevent the immeasurable losses of human lives and social properties due to earthquakes and terrorist attacks, resistance evaluation and retrofitting of civil infrastructures have become 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 years, however, terrorist attacks have also become evident as seen in the Alfred P. Murrah Building in Oklahoma City in 1995 and the World Trade Center in New York, 2001 which did not withstand the fires from terrorist attacks that have eventually induced progressive collapse of the building. The 27 May 2006 earthquake has hit the provinces of Yogyakarta and Central Java in Indonesia which lead to RC and brick building’s collapse. Besides experimental and theoretical studies, numerical simulation is another way to assist engineers to understand the nonlinear dynamic failure behavior of structure under an earthquake excitation.

Recently, the V-5 method has been proposed by Ting, et al. (2004a, 2004b) and Wang and Ting (2004). This method applies a unique approach to compute the effects of rigid motion, allowing the simulation of extremely large deformation of elastic motion structures. The V-5 method will be explained in greater detail later in this paper. It redefines a set of deformation coordinates on the element in each time step. Therefore, it removes each element’s rigid body rotations and displacements. The V-5 method adopts a convected material frame and the explicit time integration method for solving the equations of motion. This method has been successfully applied to the nonlinear motion analysis of the 2D elastic frame (Wu et al., 2006), the dynamic stability analysis of the space truss structure (Wang et al., 2006), and the elastic-plastic analysis of a space truss structure (Wang et al. 2005). The key objective of this study is to construct the V-5 method for the analysis of RC frame subjected to extremely large deformation having inelastic material properties. In this paper, analysis of collapse structures included multiple frame elements motion for large deformation and rotation from continuous states to discontinuous state. The comparison between numerical simulation of V-5 method and shake table experiments demonstrates the accuracy of V-5 method.

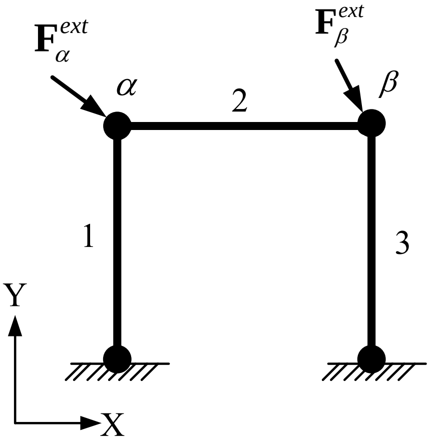


Figure 1 A plane frame structure subjected to external forces

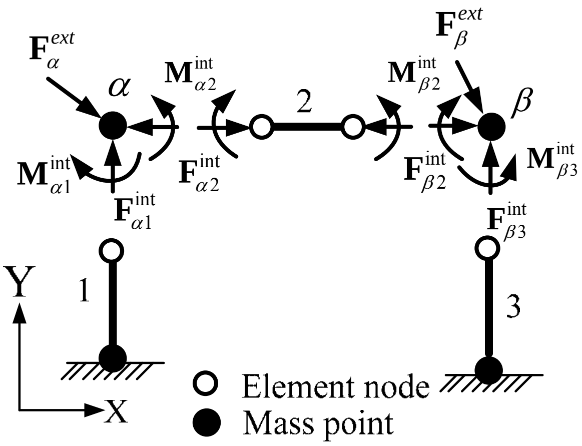


Figure 2 Discrete mass point modeling of a plane frame for the VIFE method

2. VECTOR FORM INTRINSIC FINITE ELEMENT METHOD

In this study, the V-5 method is extended in order to analyze elastic-plastic systems containing multiple deformable bodies with the following characteristics: (1) interact with each other, (2) or are discontinuous, (3) undergo large deformations and arbitrary rigid body motions. Since the conventional finite element method (FEM) is an energy-based method, it does not require the balance of forces within each element. Since these unbalanced residual forces will do some work under virtual rigid body motion it will cause inaccuracy and unconvergence of the computed results. In order to solve these problems, the V-5 method has been proposed (Ting et al. 2004a). The V-5 method includes 4 main procedures: (1) construct the equation of motion using Newton's Law at the mass points, (2) update the material frame, (3) compute the fictitious reversed rotations (4) determine the deformation coordinates. These aforementioned computation procedures have some points in common with the concept of the modern FEM. However, the key concept of the V-5 is that V-5 maintains the intrinsic nature of the original FEM. The V-5 method makes use of the strong form of equilibrium at each element. All the forces are balanced within each element. These forces are obtained from the principle of virtual work. The associated nodal displacements satisfy the compatibility condition.

2.1. Equation of motion

For discussion purposes, we have chosen a plan frame subjected to external loads as shown in Fig. 1. Figure 2 shows that in the V-5 method, the structure model is constructed by using prismatic elements and many discrete mass points. The solid circle indicates the location of the mass points. The hollow circle represents the element node. In the V-5 method, it is not required to solve the matrix equations. Hence, from the principle of virtual work, the total virtual work can be constructed from various sources. It may include the internal virtual work $\delta U_\beta^{\text{int}}$ due to element deformations, the external virtual work δW_β^{ext} due to the external forces and damping force, and the work δW_β^I associated with the mass inertia forces. Thus, for mass point β, the sum of the virtual work at time *t* is: These forces are obtained from the principle of virtual work. The associated nodal displacements satisfy the compatibility condition.

$$\delta W = \delta W_\beta^{ext} - \delta W_\beta^I + \delta U_\beta^{\text{int}} = 0 \tag{1}$$

Where

$$\delta W_\beta^{ext} = \delta \mathbf{d}_\beta \mathbf{F}_\beta^{ext} - \delta \mathbf{d}_\beta \mathbf{F}_\beta^{damp} \tag{2}$$

$$\delta W_\beta^I = \delta \mathbf{d}_\beta \mathbf{M}_\beta \ddot{\mathbf{d}}_\beta \tag{3}$$

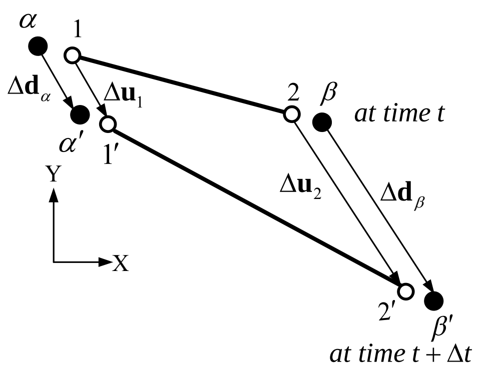
$$\delta U_\beta^{\text{int}} = \delta \mathbf{d}_\beta \mathbf{F}_\beta^{\text{int}} \tag{4}$$

Since the virtual displacement $\delta \mathbf{d}_\beta$ is not zero, the equation of motion at time t can be obtained from Eq. (1)

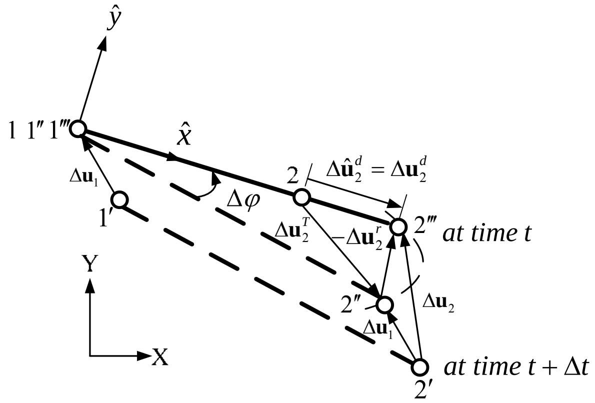
as:

$$\mathbf{F}_{\beta}^{ext} - \mathbf{F}_{\beta}^{damp} - \mathbf{F}_{\beta}^{\text{int}} = \mathbf{M}_{\beta}\ddot{\mathbf{d}}_{\beta} \tag{5}$$

From Eq. (5), it can be found that the V-5 method can solve an initial problem.



(a) Motion of mass points and the frame element



(b) The fictitious reversed rotation $\Delta\varphi$ and in time increment Δt reversed translation displacement $\Delta\mathbf{u}_1$

Figure 3 Motion of mass points and deformation of the frame element

2.2. Deformation coordinates

Since the element stresses or the internal forces should be induced from the deformations but not from the rigid body motions, it is necessary to remove the rigid body rotations from the relative displacements. For an element subjected to a reversed rotation (Ting et al. 2004), the computations of the element's net deformations (exclude the rigid body rotation) are not straight forward. Hence, a simple kinematical approach (Ting et al. 2004) has been developed and introduced as follows. The configuration of an element at time t is chosen as the material frame for the analysis (see Fig. 3a). Given a time increment Δt, the incremental displacements of the two nodes on the element at time $t+\Delta t$ are defined as ($\Delta\mathbf{u}_1$, $\Delta\mathbf{u}_2$). In order to compute the net deformations (see Fig. 3b) we first subject the frame element to a reversed translational displacement $\Delta\mathbf{u}_1$ at both ends. Then, it is subjected to a fictitious reversed rotation $\Delta\varphi$. The detailed computation of $\Delta\varphi$ can be found in (Ting et al. 2004). The aforementioned rotation induces a relative displacement vector $-\Delta\mathbf{u}_2^r$. Thus, the net deformation vector $\Delta\mathbf{u}_2^d$ for element node 2 is:

$$\Delta\mathbf{u}_2^d = \Delta\mathbf{u}_2^T + (-\Delta\mathbf{u}_2^r) \tag{6}$$

Where

$$\Delta\mathbf{u}_2^T = \Delta\mathbf{u}_2 - \Delta\mathbf{u}_1 \tag{7}$$

Thus, the net deformation vector $\Delta\mathbf{u}_2^d$ does not include the rigid body motions. For discussion purposes, a set of deformation coordinates ($\hat{x}, \hat{y}$) is specifically defined so that the axis of $\hat{x}$ is always parallel to the net deformation vector $\Delta\mathbf{u}_2^d$ at node 2 (see Fig. 3b). The origin of this deformation coordinate system is located at node 1. Thus,

$$\Delta\hat{\mathbf{u}}_2^d = \Delta\mathbf{u}_2^d \tag{8}$$

in which

$$\hat{\mathbf{e}}_1 = \frac{d\mathbf{u}_2^d}{\left|d\mathbf{u}_2^d\right|} = \begin{Bmatrix} l_1 \\ m_1 \end{Bmatrix} \tag{9}$$

$$\hat{\mathbf{e}}_2 = \begin{Bmatrix} -m_1 \\ l_1 \end{Bmatrix} \tag{10}$$

In addition, the incremental rotation of the element in the deformation coordinates can be calculated as:

$$\Delta\hat{\phi}_1 = \Delta\omega_1 - \Delta\varphi \tag{11}$$

$$\Delta\hat{\phi}_2 = \Delta\omega_2 - \Delta\varphi \tag{12}$$

Based on the net deformation vector $\Delta\mathbf{u}_2^d$ and the incremental rotations ($\Delta\phi_1$, $\Delta\phi_2$), the element internal axial force and two end bending moments can be calculated. In this way, by establishing the deformation coordinates, the net deformations and the pure strains of a frame element can be obtained. The V-5 method can effectively separate the rigid body displacements from the element displacement since it adopts a convected material frame and the aforementioned deformation coordinate to describe the element deformations.

3. MODELING OF REINFORCED CONCRETE AND DAMAGE INDEX

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. Structural material and components have damage and hysteretic behavior with deterioration under seismic excitation. In order to simulate this status, this study is added the material model of reinforced concrete in plane frame and simulated nonlinear dynamic behavior of RC frame. The material model adopts three-parameter model which is considered stiffness degrading(S_1), strength deterioration(S_2), and pinching (S_3) as shown in Fig. 4. 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). Moments and curvatures data of the frame are used to determine its damage index by Eq. (13).

$$D = \frac{K_m - K_y}{K_u - K_y} + \beta_e \frac{\int dE}{M_y K_u} \tag{13}$$

Where

K_m = maximum curvature attained during load history

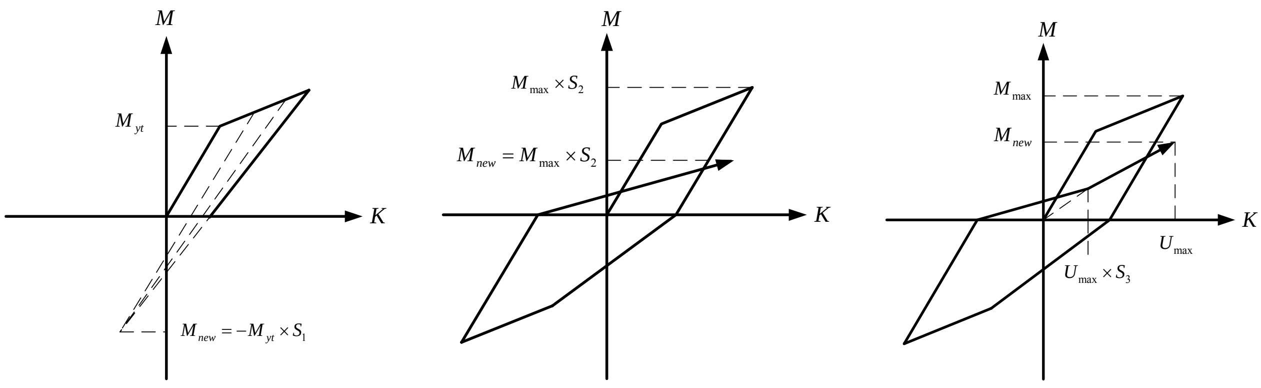
K_u = ultimate curvature capacity of section

K = recoverable curvature at unloading

β_e = strength degrading parameter

M_y = yield moment of section

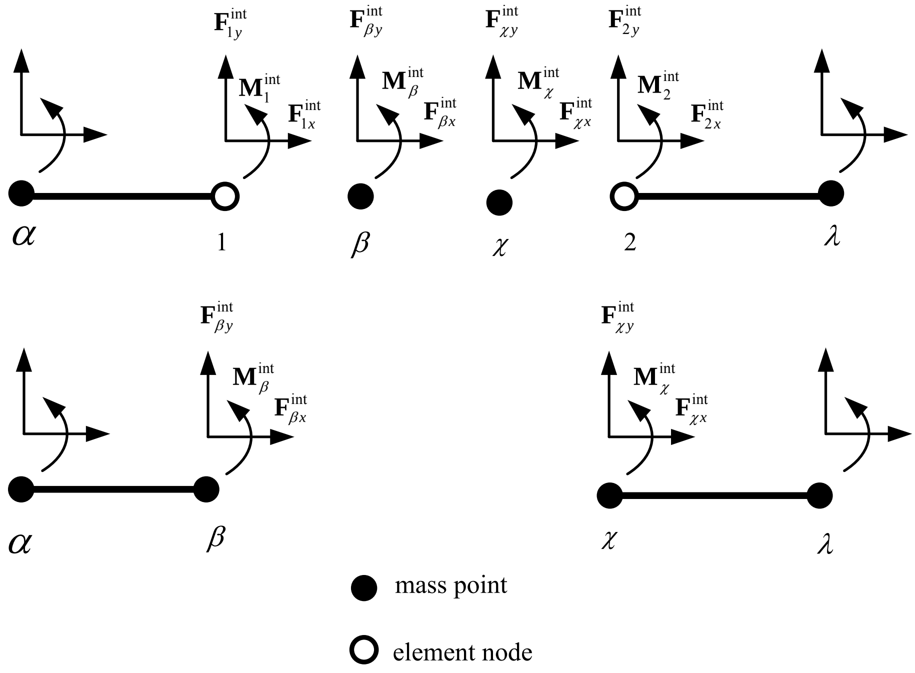
$\int dE$ = dissipated hysteretic energy



(a)Stiffness degrading factor S_1 (b) Strength deterioration factor S_2 (c) Pinching factor S_3

Figure 4 A three-parameter moment-curvature model for frame under cyclic excitation.

In the presented analysis, if the damage index of reinforced concrete frame arrive at D=0.77, we define the RC frame element is fractured. New node is added to the fracture interface to release the connectivity. The mass distribution, internal forces, external forces, nodal displacements and boundary conditions are updated for the fractured element in the presented mode(see Fig. 5).



(b) Cracking with element node and mass point

Figure 5 Simulating crack behavior in the V-5 Method

4. COMPARISON OF SHAKE TABLE EXPERIMENT AND V-5 NUMERICAL SIMULATION

This example is from shaking table tests at Center for Research on Earthquake Engineering (NCREE) in Taiwan. The V-5 method was compared with the experiment results of the shaking table tests. The examples presented here demonstrate the applicability of the proposed method in carrying out the V-5 method to analyze the collapse experiment of an RC structure under seismic excitations. In addition, an RC member was used for the section model of the moment-curvature. The adopted hysteretic model for the section model was named Polygonal Hysteretic Model (PHM), a three-parameter model. It can simulate hysteretic behavior with the stiffness degradation(S_1), the strength deterioration(S_2), and the pinching (S_3). Figure 6 shows the specimen frame on the shaking table. It is a single-story and four-column planar frame specimen. The rectangular column section is $150mm \times 150mm$. The reinforcement details of specimen frame, non-ductile columns (C1, C2) and ductile columns (C3, C4), are in reference to Wu, et al. (2008). The weights of column, beam and footings were 56 kN, 2.16 kN, and 10.98 kN, respectively. To add to the total 166.6kN of lead ballast on the beam, the planar frame specimen was subjected to two sequential earthquake accelerations during the shake table tests. The first duration of earthquake acceleration was timed at 0 second to 58 seconds (no collapse, Test 1). The second duration of earthquake acceleration was timed at 58 seconds to 83.5 seconds (collapsed, Test 2) and is shown in Fig. 7. In this study, owing from material parameters of Test 1 (no collapse), Test 2 (collapsed) behavior can be simulated. The correlation of the shake table experiment and the analysis of V-5 is plotted from Figs. 8 to 12 (no collapse) and from Figs. 13 to 17 (collapsed). The damage index of Eq. (13) is shown in Fig. 18. This example demonstrates the use of V-5 method in simulating the progressive collapse of a structure.

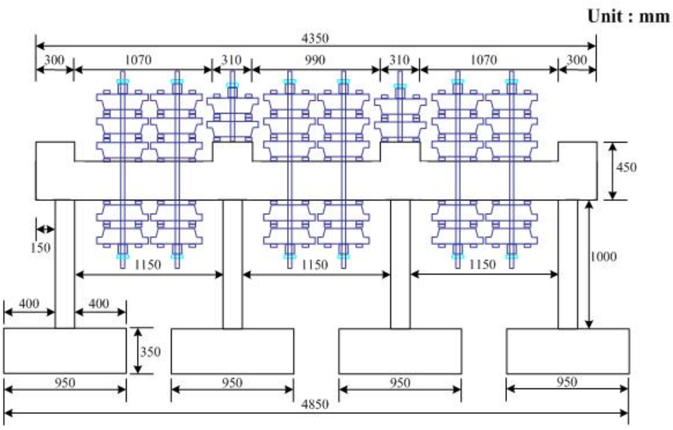


Figure 6 The specimen frame on the shaking table.

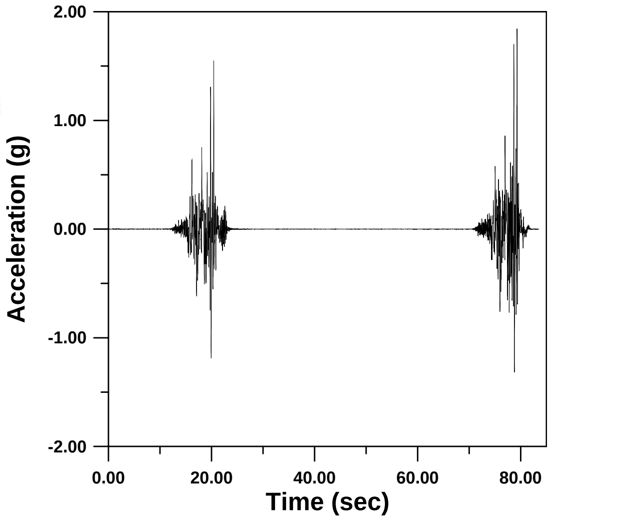


Figure 7 Earthquake acceleration on the shake table

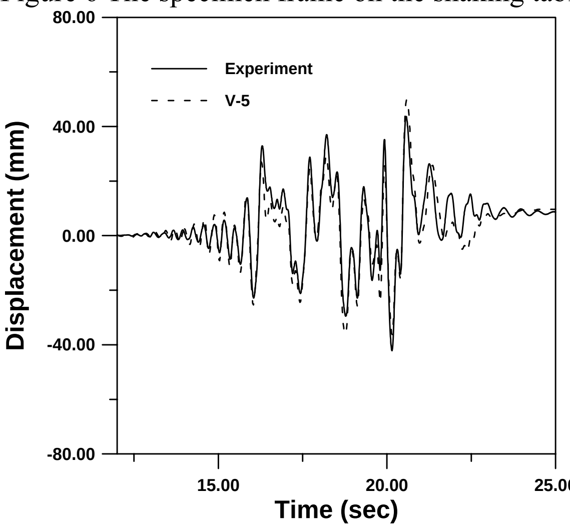


Figure 8 Displacement and time (no collapse)

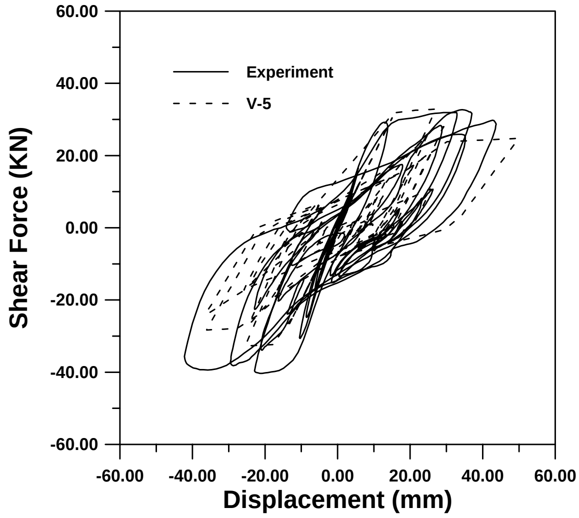


Figure 9 Shear force and displacement of column C1 (no collapse)

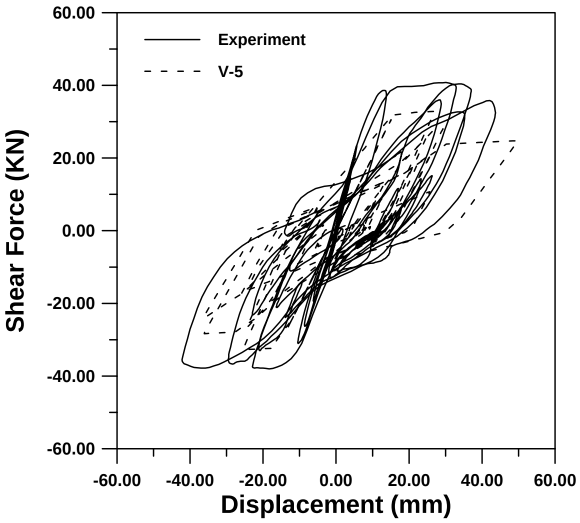


Figure 10 Shear force and displacement of column C2 (no collapse)

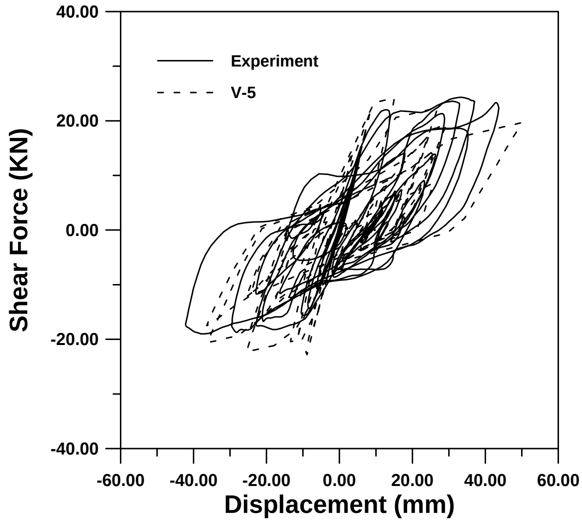


Figure 11 Shear force and displacement of column C3 (no collapse)

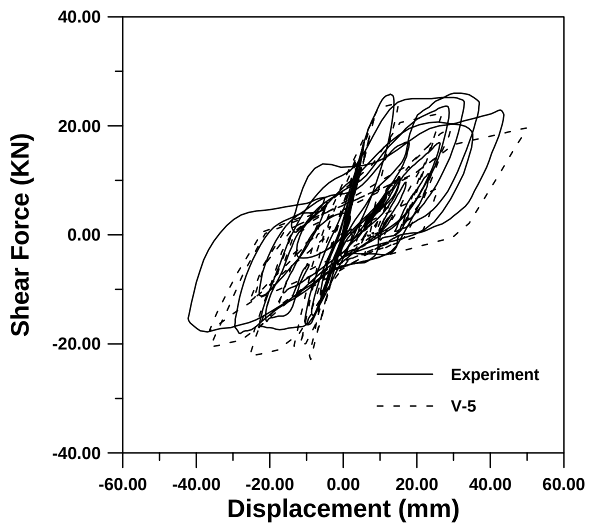


Figure 12 Shear force and displacement of column C4 (no collapse)

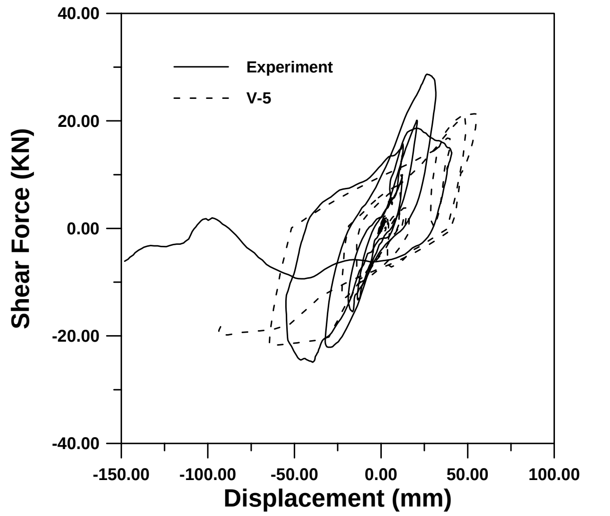


Figure 13 Shear force and displacement of column C1 (collapsed)

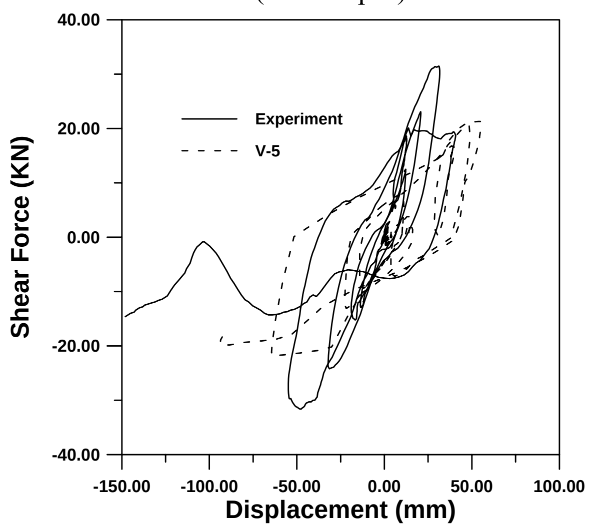


Figure 14 Shear force and displacement of column C2 (collapsed)

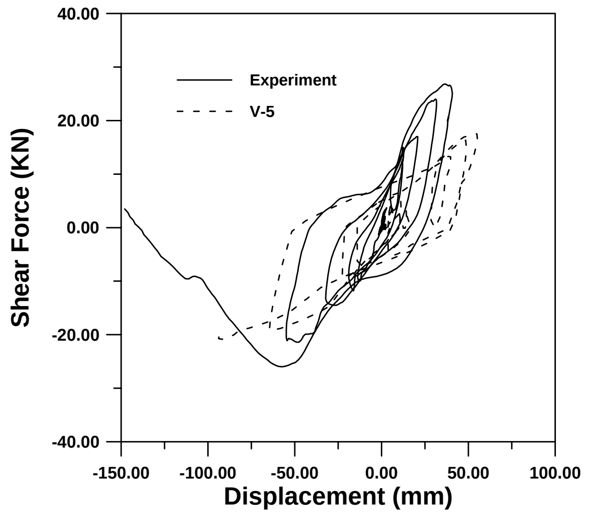


Figure 15 Shear force and displacement of column C3 (collapsed)

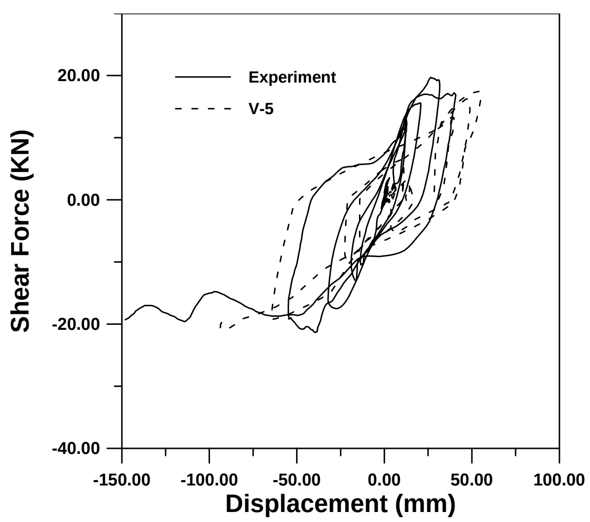


Figure 16 Shear force and displacement of column C4 (collapsed)

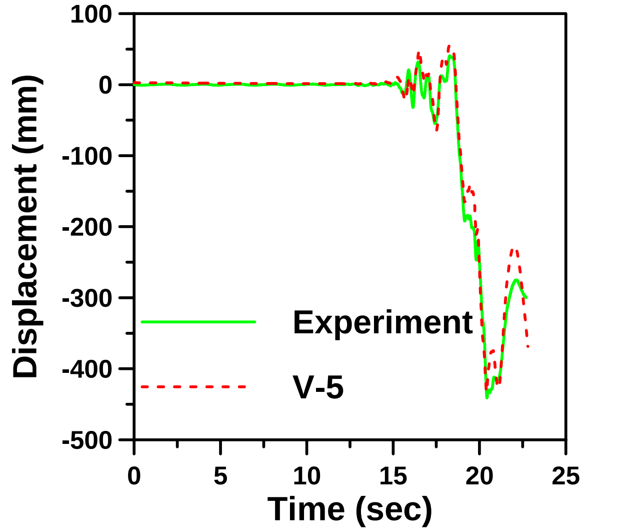


Figure 17 Displacement and time (collapsed)

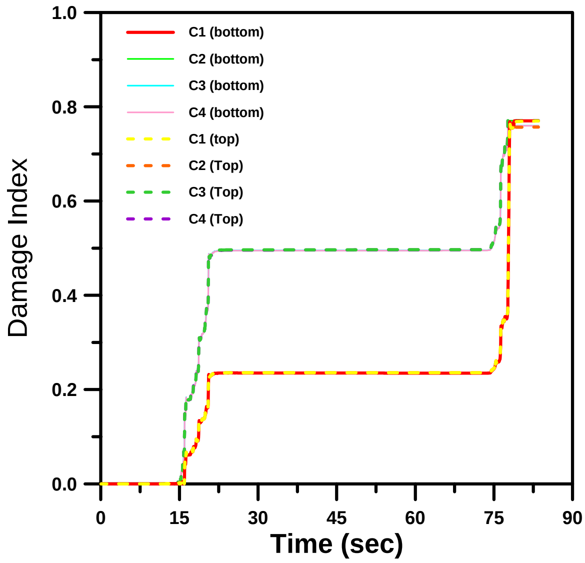


Figure 18 Time and damage index of RC column

5. CONCLUSIONS

A novel numerical method called "Vector Form Intrinsic Finite Element" (VFIFE, V-5) method for the motion analysis of space frame structure is presented. Due to some special features of V-5, 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 further developments of V-5 method on the nonlinear analysis of reinforced concrete structures can provide engineers an effective and friendly tool to analyze very complicated engineering problems.

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