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COMPUTER PROGRAM FOR THREE-DIMENSIONAL NONLINEAR DYNAMIC RESPONSE ANALYSIS OF SEISMICALLY-ISOLATED BUILDINGS

Masaru KIKUCHI [1] and Koichi WATANABE [2]

SUMMARY

This paper presents a recently enhanced structural analysis computer program, DAC3N. The program has been recently upgraded to include special capabilities for seismically-isolated structures. The enhanced features of the program make it an effective and useful tool for practical design purposes. The accuracy of the seismic response prediction for an isolated structure strongly depends on the modeling methods used for the isolation devices. The paper describes the general features of the program and the modeling methods for various types of isolation devices. Some application examples are also presented.

INTRODUCTION

Effective and economical structural design for earthquake resistance requires accurate prediction of the seismic behavior of both isolated and fixed base structures. Each major earthquake contributes to the engineer's understanding of building response and often leads to higher standards for performance and more complex analysis requirements. The program DAC3N was originally developed by the authors for the three-dimensional nonlinear dynamic analysis of structures to satisfy such demands.

The design and analysis requirements for structures with seismic isolation, energy dissipation, or active control devices can be quite restrictive. The structural engineer is often faced with a problem that can not be solved using existing, general purpose commercial programs. This is especially true when a new type of structural device is intended to be used in the design. The engineer has to evaluate the performance of those devices as early as possible in the design process. DAC3N has been an effective and useful tool for such practical design tasks. Since DAC3N was first released fifteen years ago, it has been continuously upgraded. The current version is noticeably enhanced to include special capabilities for seismically-isolated structures. This paper describes the development of the computer program DAC3N and the analytical modeling methods for the nonlinear dynamic analysis of seismically-isolated structures as one of the enhanced features of the program.

[1] Assoc. Prof., Graduate School of Engineering, Hokkaido Univ., Dr. Eng.
[2] Research Engineer, Institute of Technology, Shimizu Corp., M. Eng.

OVERVIEW OF PROGRAM DAC3N

The program DAC3N was developed for the nonlinear dynamic time history analysis of three-dimensional structures. The development of DAC3N started in 1986. Improvements to and extensions of the program's capabilities have been continuously pursued. One of the main concepts of the program is the easy addition of new element and hysteresis libraries by researchers or users of the program. The modular design of DAC3N means that the user need not write duplicate program components and can easily combine their original methods with the libraries previously developed by other users. The program also offers a sophisticated computational capability developed by the researchers.

The element library contains: (1) linear spring; (2) nonlinear spring; (3) biaxial nonlinear spring; (4) triaxial nonlinear spring; (5) nonlinear truss bar; (6) simple nonlinear beam; (7) beam with nonlinear concentrated flexural springs at the ends; (8) biaxial nonlinear column; (9) triaxial nonlinear column; (10) linear plate shell; (11) nonlinear shear wall; (12) nonlinear ground spring; (13) active control device; (14) nonlinear viscous damping. Fig. 1 shows some of the element types in the program.

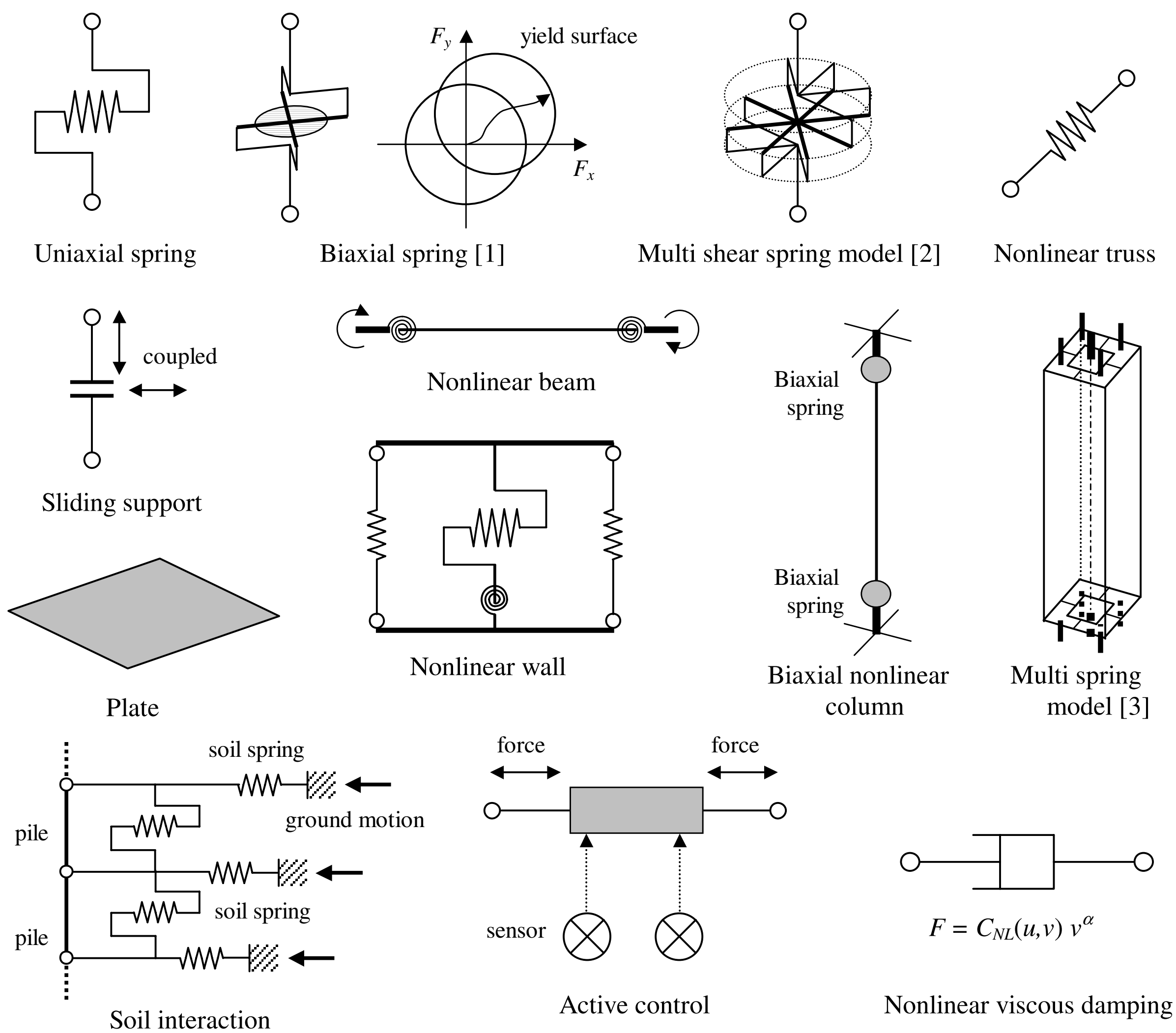


Fig. 1 DAC3N element library

The hysteresis library contains: (1) bilinear; (2) trilinear; (3) Ramberg-Osgood model; (4) Takeda model; (5) seismic isolator (high-damping rubber and lead rubber bearing); (6) steel damper; (7) viscous damper (8) R/O or H/D model for soil nonlinearity. Fig. 2 shows some of the hysteresis types in the program.

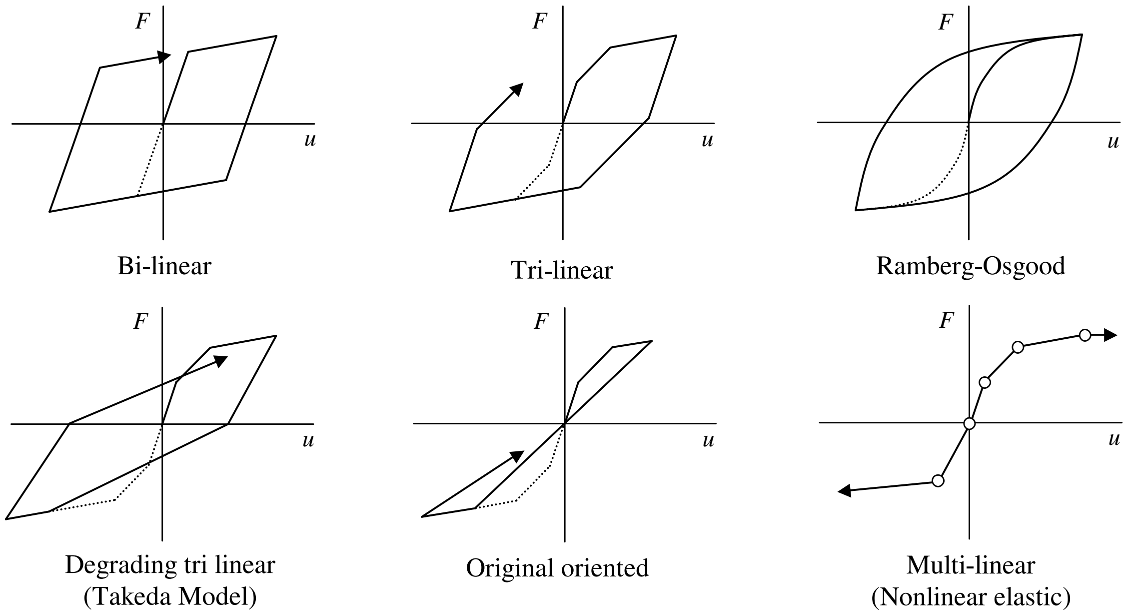


Fig. 2 DAC3N hysteresis library

The program includes the following analysis options: (1) nonlinear push-over analysis for any combination of element and static nodal loads; (2) nonlinear dynamic analysis for any six degree-of-freedom ground motion; (3) nonlinear dynamic analysis for any six degree-of-freedom definition of nodal loads; (4) mode shapes and natural frequencies in the initial elastic state. By use of the element and hysteresis libraries the program permits the user considerable flexibility in modeling a variety of structures, ranging from a simple stick model to a three-dimensional frame model, as shown at Fig. 3.

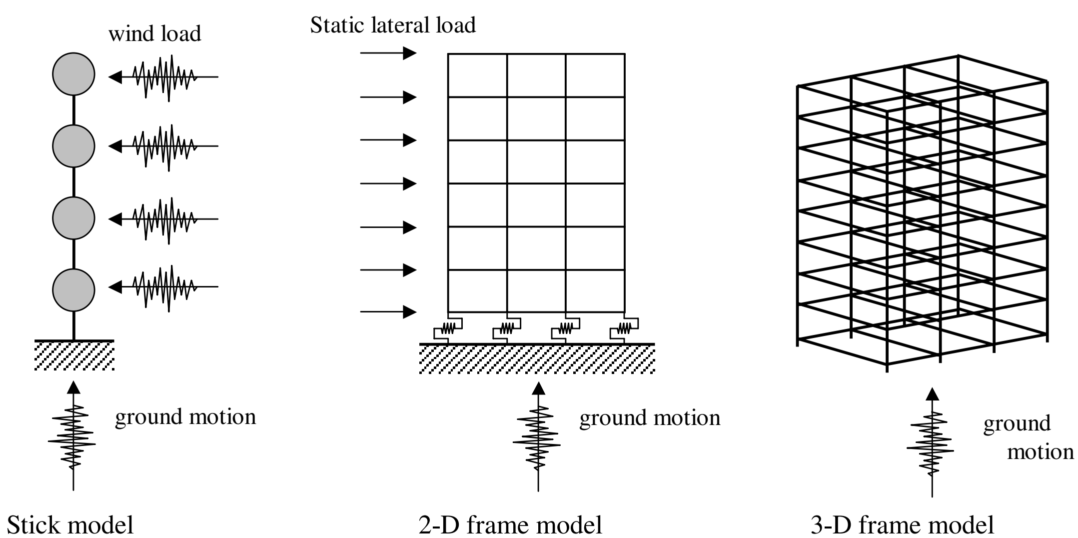


Fig. 3 Structural modeling methods

METHOD OF SOLUTION

This section describes the numerical solution shceme used in DAC3N (Fig. 4). The solution scheme is similar to that of the finite element analysis program ADINA developed by Bathe [4]. Implicit time integration is employed in dynamic analysis. The equation of motion is:

$$\mathbf{M\ddot{u}} + (\mathbf{C}_L + \mathbf{C}_{NL})\mathbf{\dot{u}} + \mathbf{K}_L\mathbf{u} + \mathbf{F}_{NL}(\mathbf{u}) = \mathbf{R} \tag{1}$$

in which **M** is the mass matrix, $\mathbf{C_L}$ is the damping matrix for linear viscous elements, $\mathbf{C_{NL}}$ is the damping matrix for nonlinear viscous elements, and $\mathbf{K_L}$ is the stiffness matrix for linear elements, $\mathbf{F_{NL}}$ is the force vector for nonlinear elements and **R** is the force vector for externally applied nodal point loads. $\mathbf{F_{NL}}$ can be expressed as a function of nodal displacements.

The basic equations to be solved are

$$\mathbf{f}(\mathbf{u}^*) = \mathbf{o} \tag{2}$$

where

$$\mathbf{f}(\mathbf{u}^*) = \mathbf{R} - \left\{\mathbf{M\ddot{u}}^* + (\mathbf{C}_L + \mathbf{C}_{NL})\mathbf{\dot{u}}^* + \mathbf{K}_L\mathbf{u}^* + \mathbf{F}_{NL}(\mathbf{u}^*)\right\} \tag{3}$$

A Taylor series expansion of $\mathbf{f}(\mathbf{u}^*)$ above the solution $\mathbf{u}^*$ gives

$$\mathbf{f}(\mathbf{u}^{(i-1)}) + \left[\left.\frac{\partial \mathbf{f}}{\partial \mathbf{u}}\right|_{\mathbf{u}^{(i-1)}}\right](\mathbf{u}^{(i)} - \mathbf{u}^{(i-1)}) = \mathbf{0} \tag{4}$$

where high-order terms are neglected and the superscript (i-1) is used to denote the (i-1)st approximation to the solution vector $\mathbf{u}^*$.

Newmark's method is introduced, as follows:

$$^{t+\Delta t}\mathbf{\ddot{u}} = a_0(^{t+\Delta t}\mathbf{u} - {}^t\mathbf{u}) - a_1\,{}^t\mathbf{\dot{u}} + a_2\,{}^t\mathbf{\ddot{u}} \tag{5}$$

$$^{t+\Delta t}\mathbf{\dot{u}} = {}^t\mathbf{\dot{u}} + a_3\,{}^t\mathbf{\ddot{u}} + a_4\,{}^{t+\Delta t}\mathbf{\ddot{u}} \tag{6}$$

where

$$a_0 = \frac{1}{\beta\Delta t^2}, \quad a_1 = \frac{1}{\beta\Delta t}, \quad a_2 = 1 - \frac{1}{2\beta}, \quad a_3 = (1-\gamma)\Delta t \quad a_4 = \gamma\Delta t \tag{7}$$

In Eq. (7) the average acceleration method is applied in the case of γ=1/2 and β=1/4, or the linear acceleration method is applied in the case of γ=1/2 and β=1/6

By substituting Eqs. (5) and (6) into Eq.(3), we obtain

$$\frac{\partial \mathbf{f}}{\partial \mathbf{u}} = -\frac{1}{\beta\Delta t^2}\mathbf{M} - \frac{\gamma}{\beta\Delta t}(\mathbf{C}_L + \mathbf{C}_{NL}^{(i-1)}) - (\mathbf{K}_L + \mathbf{K}_{NL}^{(i-1)}) \tag{8}$$

in which $\mathbf{K}_{NL}^{(i-1)}$ is the tangent stiffness matrix for nonlinear elements in iteration (i-1).

Thus Eq. (4) yields

$$\mathbf{K}^*\Delta\mathbf{u}^{(i)} = \Delta\mathbf{P} \tag{9}$$

where

$$\mathbf{K}^* = (\mathbf{K}_L + \mathbf{K}_{NL}^{(i-1)}) + \frac{\gamma}{\beta\Delta t}(\mathbf{C}_L + \mathbf{C}_{NL}^{(i-1)}) + \frac{1}{\beta\Delta t^2}\mathbf{M} \tag{10}$$

$$\Delta\mathbf{u}^{(i)} = {}^{t+\Delta t}\mathbf{u}^{(i)} - {}^{t+\Delta t}\mathbf{u}^{(i-1)} \tag{11}$$

$$\Delta\mathbf{P} = {}^{t+\Delta t}\mathbf{R} - \left\{\mathbf{M}\,{}^{t+\Delta t}\mathbf{\ddot{u}}^{(i-1)} + (\mathbf{C}_L + \mathbf{C}_{NL})\,{}^{t+\Delta t}\mathbf{\dot{u}}^{(i-1)} + \mathbf{K}_L\,{}^{t+\Delta t}\mathbf{u}^{(i-1)} + \mathbf{F}_{NL}({}^{t+\Delta t}\mathbf{u}^{(i-1)})\right\} \tag{12}$$

Either the full or modified Newtown-Raphson iteration method is available in the program to solve Eq. (9) numerically by considering the nonlinearity and load (or time) increment of the analytical cases.

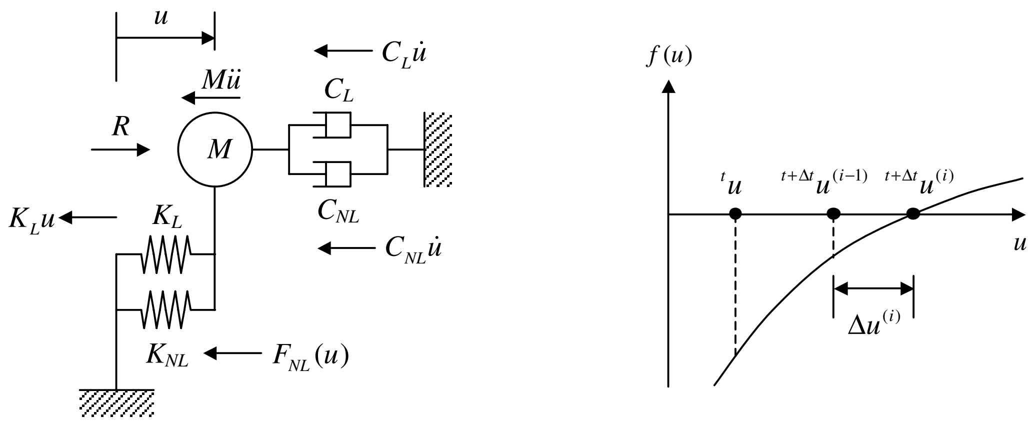


Fig. 4 One-dimensional example for nonlinear system

ISOLATION SYSTEM MODELING

The accuracy of the seismic response prediction for an isolated structure strongly depends on the modeling method used for the isolation device. Analytical hysteretic models for a number of isolation devices have been proposed previously by one of the authors and validated experimentally through earthquake simulator tests [5]. DAC3N incorporates these well-developed isolation models and currently allows for: (a) detailed modeling of the horizontal force-deformation properties of high-damping rubber bearings, lead rubber bearings, sliding supports, and steel dampers, and (b) detailed modeling of the vertical axis properties of elastomeric bearings.

The relationship between horizontal force and deformation of seismic isolation devices with hysteretic damping, such as high-damping rubber bearings, lead rubber bearings, sliding supports and steel dampers can be expressed by the combination of an elastic component of force, F_1, and a hysteretic component, F_2 and is given by Eqs. (13)-(15). These equations were obtained by evaluation of a large number of experimental results [5].

$$F = F_1 + F_2 \tag{13}$$

$$F_1 = \frac{1}{2}(1-u)F_m\left\{x \pm |x|^n\right\} \tag{14}$$

$$F_2 = \pm uF_m\left\{1 - 2e^{-a(1\pm x)} + b(1\pm x)e^{-c(1\pm x)}\right\} \tag{15}$$

where F_m is the peak force on the skeleton curve, x is the normalized displacement ($x= X/ X_m$) and X_m is the peak displacement on the skeleton curve. In Eq. (14) the parameter n specifies the stiffening. The parameter u is the ratio of force at zero displacement, F_u, to F_m ($u = F_u / F_m$). The parameters a and b are calculated from Eqs. (16) and (17), which are derived assuming that the analytical and experimental hysteresis loop areas are equal:

$$\frac{1-e^{-2a}}{a} = \frac{2u - \pi h_{eq}}{2u} \tag{16}$$

$$b = c^2 \left[\frac{\pi h_{eq}}{u} - \left\{ 2 + \frac{2}{a}\left(e^{-2a} - 1\right) \right\} \right] \tag{17}$$

where h_{eq} is the equivalent viscous damping ratio. The parameter c is a pre-selected constant which specifies the shape of the hysteresis loop.

Eq. (16) cannot be solved in closed form for parameter a, and thus must be solved numerically. All of the parameters that control the shape of the hysteresis loop are updated using Eqs. (16) and (17) when load reversal occurs from the skeleton curve. Fig. 5 shows typical hysteresis loops given by Eqs. (13)-(15). The shapes of these hysteresis loops are typical of that of seismic isolation devices with hysteretic damping. The nonlinear stiffening behavior observed in the elastomer at large deformations can be represented as shown in the right-hand plot of Fig. 5. Thus, the model expressed by Eqs. (13)-(15) can easily capture the important hysteretic features of various types of isolation devices.

The above formulae were derived for application to steady-state hysteresis behavior for isolation devices. Masing Rule is applied to fully define the force under randomly-varying displacement conditions for earthquake response analyses in the program [6].

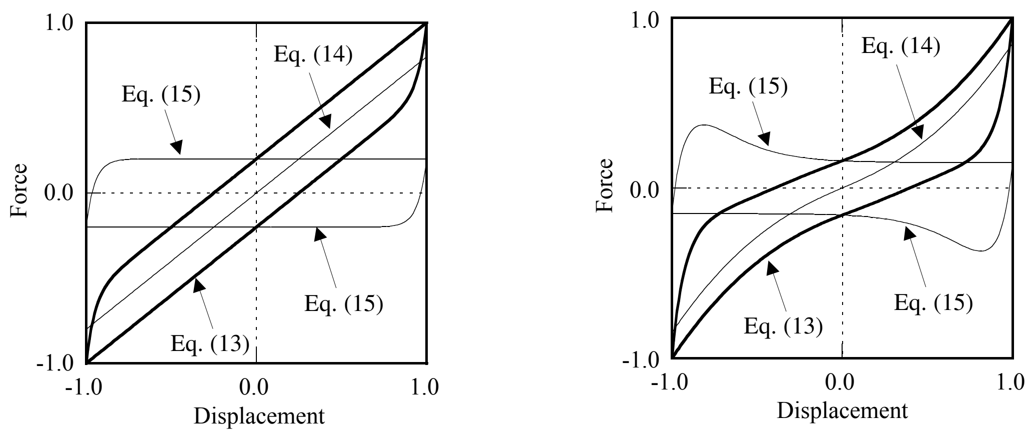


Fig. 5 Normalized hysteresis loops of isolation devices for horizontal direction
(left: low shear stain level, right: high shear starin level)

For the purpose of applying isolation systems to a variety of buildings such as medium-rise or high-rise buildings, DAC3N has a hysteresis model to represent the vertical direction properties of elastomeric bearings. Such buildings could potentially generate overturning moments that would cause uplift off some isolators. It has generally been accepted that elastomeric isolation bearings should not be subjected to tension loads due to their intrinsic strong stiffness nonlinearity and low capacity under tension forces. A new hysteresis rule for the vertical mechanical properties of elastomeric bearings was proposed by one of the authors for the purpose of simulating the uplift behavior of bearings in isolated buildings [7]. It was also obtained by the insight into the experimental results of high-damping rubber bearings. The rule consists of three types of loading states, as shown in Eqs. (18)-(20):

(1) Loading and unloading in compression region

$$F = K_c X \tag{18}$$

(2) Loading in tension region

$$F = K_y (X - X_s) + F_y \left\{ 1 - e^{-\lambda \frac{K_t - K_y}{f_y}(X - X_s)} \right\} \tag{19}$$

(3) Unloading in tension region

$$F = \frac{F_r + F_t}{2} + \frac{K_r X_i - F_i}{2}\left(X - \frac{X_r + X_t}{2}\right)^3 + \frac{3F_i - K_r X_i}{2X_i}\left(X - \frac{X_r + X_t}{2}\right) \tag{20}$$

where K_c is the compression stiffness, K_t is the initial tension stiffness, K_y is the yielding tension stiffness, K_r is the unloading stiffness in tension, F_y is the tension yielding force, X_s is the remaining deformation due to nonlinearity in tension and γ is the parameter for stiffness degradation due to load reversals. The other parameters are calculated as follows:

$$F_i = \frac{F_r - F_t}{2}, \quad X_i = \frac{X_r - X_t}{2}, \quad F_t = -\lambda F_r, \quad X_t = \frac{F_t}{K_c} \tag{21}$$

Fig. 6 shows the hysteresis loops given by Eqs. (18)-(20), compared with test results. The model is shown to accurately simulate the vertical force-displacement relationship for an elatomeric bearing.

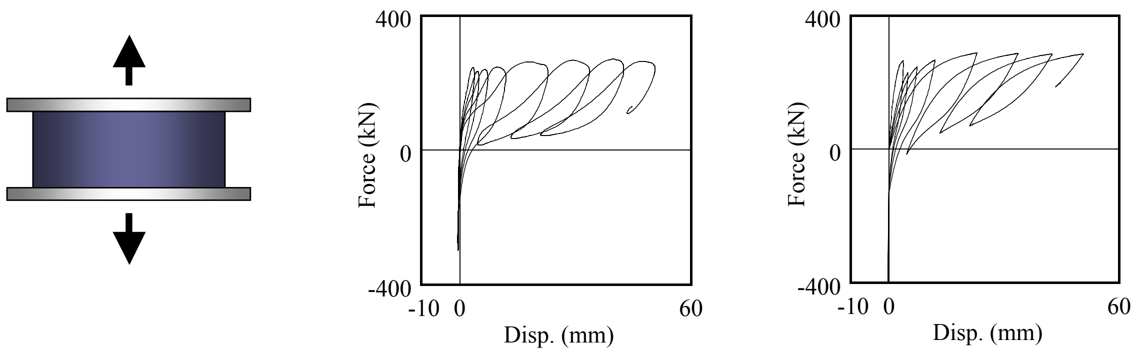


Fig. 6 Vertical direction hysteresis behavior for elastomeric rubber bearings
(left: experimental, right: analytical)

APPLICATION EXAMPLES

DAC3N has been utilized for the structural design of more than 40 seismically-isolated buildings to date. Some representative application examples are described here.

An isolated building with large eccentricity

A common architectural design objective is to achieve substantial, even exhilarating, open spaces within buildings, but this is often contrary to preferred structural design configurations for earthquake resistance. A typical consequence of these conflicting design objectives is an imbalance between the center of mass and the center of rigidity of a structure. Seismic isolation systems can provide an effective solution for this type of problem.

DAC3N was applied to the design of a new research laboratory building shown in Fig. 7. There is a large stairwell atrium from the first to

Fig. 7 Building perspective view

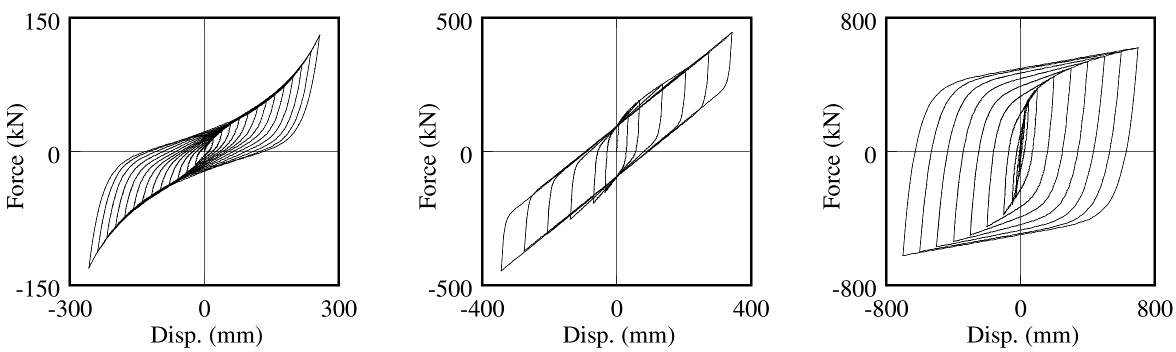
the seventh stories at the center of the building. The lower three stories of the south portion of the building are of open-frame configuration, with glass used to minimize the boundary between the atrium and the outside. A significant torsional response was anticipated because of the large eccentricity. The main objective in the design of the isolation system, consisting of high-damping rubber bearings and sliding bearings, was to achieve the smallest possible eccentricity. A three-dimensional frame model was used to evaluate the detailed torsional response. The eccentricity ratio of overall system was kept at 0.004, in spite of the large eccentricity of 0.19 in the superstructure. This configuration reduced the torsional response considerably. A detailed study of this building is described in reference [8].

Seismic retrofit of an historic building

Seismic isolation is one of the most effective techniques to protect existing buildings from damaging earthquakes. It can minimize the need for superstructure reinforcement making it particularly suitable for the retrofit of historic buildings.

The Osaka City Central Public Hall shown in Fig. 8, was built in 1918 and is an important symbolic heritage building in Osaka, Japan. It is a three-story with one basement level, steel and masonry structure. It has been used for such cultural activities as concerts, shows and conferences. In 1995, the Osaka city council made a decision to preserve the building using seismic isolation. The seismic rehabilitation of the building has recently been completed, and it is now the most notable application of seismic isolation retrofit in Japan [9].

Fig. 8 Osaka City Central Public Hall
(Photo credit: SIE. Inc.)



(a) High-damping rubber bearing (b) Lead rubber bearing (c) Steel damper

**Fig. 9 Hysteresis loops of isolation and evergy dissipation devices,
Osaka City Central Public Hall**

The Osaka City Central Public Hall isolation system uses 16 low modulus high-damping rubber bearings, 46 lead rubber bearings, and 20 steel dampers. An important aspect of the structural design for the isolation system was a precise evaluation of the mechanical properties of the three types of devices. New hysteresis models were developed to model the devices. Fig. 9 shows the analytically obtained hysteresis loops that were proposed by one of the authors. Good results were obtained for all three types of devices [10]. Seismic response analyses were conducted using DAC3N with the new hysteresis models. The response given by existing models, such as a bi-linear model, were mostly conservative. Accurate evaluations of the performance of the isolation devices identified the most effective and economical configuration for the isolation system.

An isolated building on a soft soil site

The concept of seismic isolation is to uncouple the building from the ground motion and to move the period of the structure away from the predominant period of the ground motion by introducing flexible elements in the structural system. Therefore the effectiveness of the isolation system for buildings on soft soil site is in general not assured and requires additional analysis.

The design for the new building shown in Fig. 10 started on the basis of creating a new style laboratory facility in the urban area of Tokyo. The soil conditions at the site seemed not to be appropriate for the isolation system. One of the solutions for the soft soil condition was to provide a longer isolation period. The soil-pile-structure interaction model shown at Fig. 11 was used for the seismic response analyses for the design. An intensive study utilizing DAC3N concluded that only six lead rubber bearings were necessary to support the superstructure and achieve the appropriate isolation characteristics. The isolation system consists of three 1100mm and three 1000mm diameter bearings. A mega-truss system is used to distribute the building weight to the six bearings. The isolated period of the building is 4.0 seconds at 200 % shear strains in the bearings.

Fig. 10 Perspective view of the laboratory

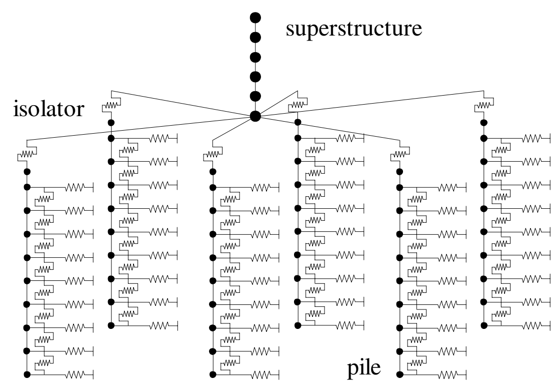


Fig. 11 Soil-pile-structure interaction model

CONCLUSIONS

DAC3N is a program for the nonlinear dynamic time history analysis of three-dimensional structures. Since the DAC3N project started in the late 1980s, the program has been continuously developed and in its current form is a powerful system for both research activity and practical design. The most important aspect of the program is the easy implementation of new element and hysteresis libraries by end users. The participation of researchers with a variety of backgrounds, as well as designers, has resulted in continual improvement and ongoing extensions of the program's analytical capabilities.

This paper has described the specialized features that have been developed for the analysis of seismically-isolated structures. The features of DAC3N make it an effective and useful tool for research and practical design purposes. The program has been used for the design of more than forty isolated building projects, three of which have been described to show the versatility of the program.

ACKNOWLEDGEMENTS

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