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EFFICIENT APPLICATION OF THE SECANT METHOD FOR CAPTURING THE PEAK RESPONSE OF COMPLEX MULTI-STORY BUILDINGS

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SUMMARY

The Secant Method is an iterative method in which the peak displacement response of a structure or structural component is determined from linear dynamic analyses of a model whose stiffness is updated to reflect a computed degree of degradation that is consistent with the computed peak displacement. Numerous descriptions of the Secant Method and related procedures exist in the literature. Division 95 of the City of Los Angeles Building Code, for example, includes a formulation of the Secant Method that is specifically intended for evaluation and rehabilitation of infill frame buildings with limited ductility. In the Secant Method, the degree of degradation of a structure is derived from the secant as determined from nonlinear force-displacement relationships for the structure as a whole or from appropriate sub-assemblies and this information is substituted into the linear dynamic analysis environment. In this way, the dynamic analysis model is updated to approximate intermediate states of degradation until a rational and consistent convergence in each sub-assembly as well as the whole structure is achieved. The Secant Method can be unwieldy, however, when applied to multistory complex structures, due to the involvement of a number of modes in their dynamic response and due to the requirement that convergence be achieved for the system as a whole and for its various sub-assemblies. In this paper, we explain the basic Secant Method, apply it to complex multi-story buildings, and describe an iterative routine that facilitates capturing higher mode and torsional response while greatly reducing the number of iterations required to achieve convergence.

BACKGROUND

Substitute-Structure Method

The Secant Method is one of a number of analytical procedures available to earthquake engineers today for predicting the earthquake performance of structures. Sozen has been credited with having developed progenitor procedures, the Substitute Damping Method [1] and the Substitute-Structure Method [2], from which the Secant Method can be derived [3]. A signature of these methods is their reliance upon the

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generally accepted observation that the peak inelastic response of a structure during an earthquake can be represented by an equivalent linear elastic model that is derived from an undamaged model. In the Substitute-Structure Method (SSM), equivalence is obtained by incorporating, on an element-by-element basis, modifications to an undamaged frame model which are intended to account for the reduced 'effective' stiffness of damaged elements and for changes in modal damping ratios. Stiffness modifications are based upon element moment-curvature relationships and assumed 'damage ratios', which are analogous to ductility, for each element (Figure 1). Because SSM is a design method for reinforced concrete frame systems, the 'damage ratios' are pre-set by the analyst as a function of the level of damage that is tolerable, based upon the element proportioning, reinforcing, detailing, etc. These pre-set tolerable 'damage ratios' permit quantification of element secant stiffnesses from their individual moment-curvature relationships, which are substituted directly into the elastic frame model in lieu of the element initial elastic stiffnesses.

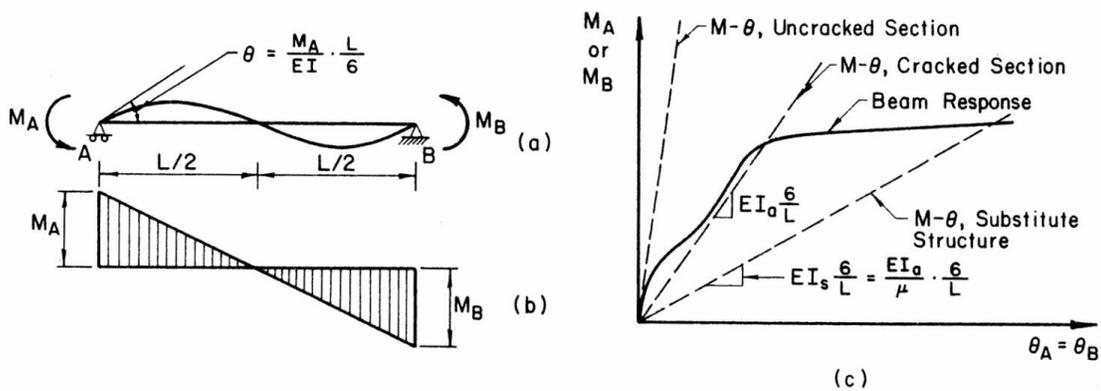


Figure 1. Interpretation of damage ratio in Substitute-Structure Method by Shibata and Sozen [1].

Once the model is developed, modal damping ratios are computed and the model is subjected to linear dynamic response spectrum analysis using a smoothed design response spectrum. The Substitute Damping Method (SDM) is similar to SSM in concept but was developed for single degree of freedom systems. Though neither SDM nor SSM ever developed a broad following by engineering practitioners, the premise upon which they are based pervades a great deal of present-day earthquake engineering practice.

Capacity Spectrum Method

The Capacity-Spectrum Method (CSM), developed by Freeman, preceded the development of SSM but also fundamentally relies on the expectation that elastic systems can be defined that capture significant aspects of inelastic behavior. [4, 5] CSM was not a design method, as was SSM, at its conception but instead was developed to facilitate the evaluation of the expected performance of existing buildings. CSM also differed from SSM at its conception in that it was intended to have applicability to all types of structural systems and materials. CSM is a graphical inelastic analysis procedure in which the capacity of a structure is determined via a pushover analysis, performed by using either step-by-step elastic methods or by nonlinear analysis (Figure 2).

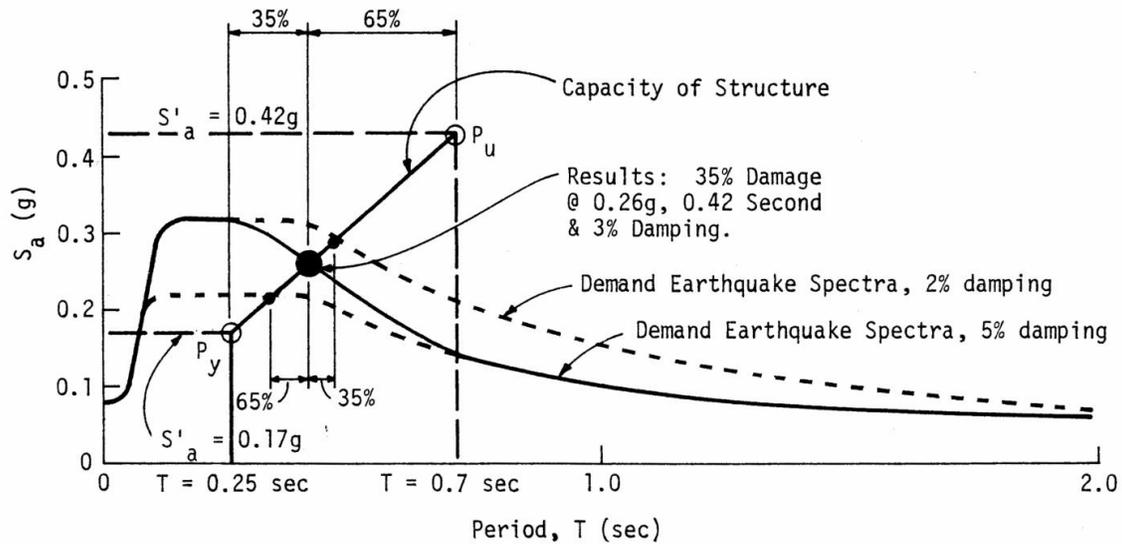


Figure 2. Capacity Spectrum Method from Freeman [5].

Unlike SSM which anticipates the final damaged state at the outset of the dynamic analysis, the CSM pushover analysis requires softening the structural model on an element-by-element basis to reflect the appropriate sequencing of the onset of inelasticity and plasticity of individual elements. In CSM, this pushover-based capacity curve is plotted in Force-Displacement space, traditionally spectral acceleration vs. period (i.e., S_a vs. T), and reconciled with a demand curve – a response spectrum which need not be smoothed but which has been modified to reflect the level of energy dissipation appropriate to the particular structure, failure mode, and earthquake. In the years since its introduction, the principles of CSM have been validated, and at the same time extended, via their application to a broad class of problems. For example, CSM was employed as a design method for essential buildings using design response spectra [6]; is routinely used to evaluate the performance of existing buildings in past earthquakes using response spectra from ground motion records instead of design response spectra [7]; and, has been used to evaluate the response of structures with significant higher mode behavior [8]. CSM has also evolved from a procedure presented in a traditional S_a vs. T space into a linear tri-partite space defined by S_a , S_d and T known as ADRS format [9], and also with reference to the Earthquake Engineering Intensity Scale [10].

CSMIP Data Interpretation Project

Studies performed as part of the Data Interpretation Project (DIP) of the California Strong Motion Instrumentation Program also contributed to the development of the Secant Method [11]. These studies addressed the behavior of existing instrumented buildings during three earthquakes in the early 1990s and aimed to analytically simulate their recorded responses. Four plan and vertically irregular unreinforced masonry infill buildings, which varied in height from 5 to 12 stories, were analyzed. As with both SSM and CSM, the DIP analyses were premised upon, and sought to validate, the assumption that elastic models using effective stiffnesses could provide an adequate dynamic representation of a structure responding inelastically to an earthquake. Similar to SSM, these studies employed two distinct analytical procedures: in this case, two-dimensional nonlinear analyses for estimating secant stiffness of the infill and of the confining frames at interstory displacements which were pre-estimated from the displacement histories obtained from the CSMIP records and three-dimensional linear elastic time history analysis employing the pre-determined secant stiffness of the infill, modeled as diagonal struts. However, due to the fact that the DIP studies were intended to simulate recorded building behavior under a known

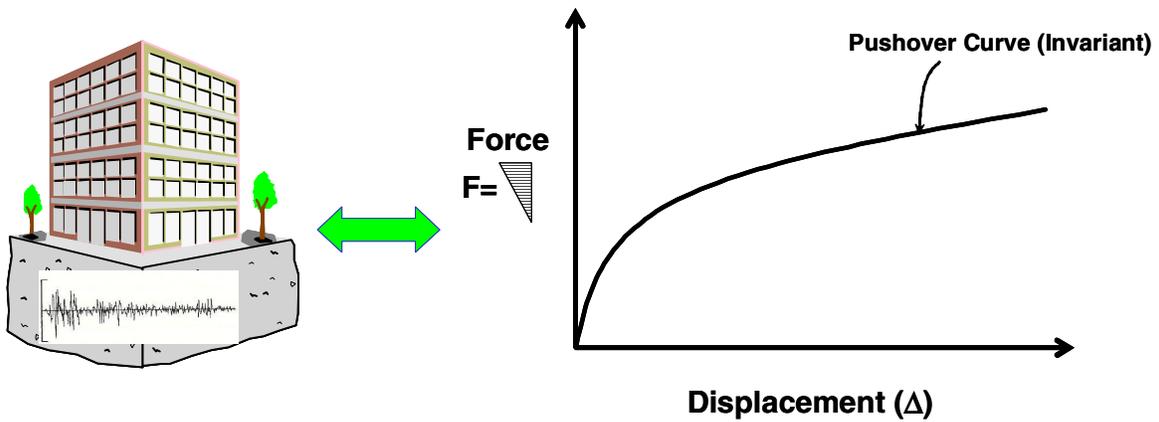
excitation rather than some future design event, the DIP method requires something that is not required by SSM – namely, consistency between the displacements predicted by the linear elastic time history analysis and the displacements upon which the pre-determined stiffnesses are based. Therefore, the DIP method includes the additional step of iterating between the two analytical environments in order to achieve convergence between the predicted displacements and the assumed stiffness, since without convergence the solution is not theoretically valid. In the published DIP studies, it is reported that the estimated secant stiffnesses of the infill and frame elements and the damping ratios indeed required adjustment in the three-dimensional analyses in order to ‘match’ the building periods and displacements discerned in CSMIP records, but the procedure for making the adjustments and performing the iterations was not described in detail. For cases where displacement histories of the structure being analyzed are not available, an iterative procedure is recommended in which initial interstory displacements are assumed and revised as indicated by the dynamic analyses.

Division 95

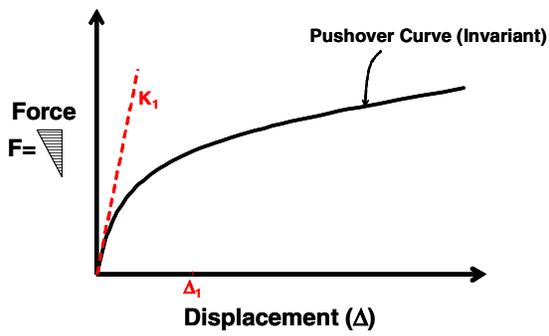
Chapter 95 of the 1996 edition of the City of Los Angeles Building Code, entitled “Voluntary Earthquake Hazard Reduction in Existing Concrete Buildings and Concrete Frame Buildings with Masonry Infill” [12], includes a Dynamic Lateral Analysis Procedure that describes what has come to be known as the Secant Method and is a clear descendant of the above-described methods. Chapter 95, often referred to as Division 95, prescribes voluntary standards for investigating the seismic adequacy of existing masonry infill frame buildings of limited ductility. The Division 95 standards are also to be applied to the design of seismic improvements of this class of buildings. In addition to sharing the fundamental premise of the methods already described, Division 95 explicitly incorporates many of the features of those methods, for example, combining the displacement-based design intent of SSM with the requirement that consistency between the predicted behavior and the assumed behavior be analytically verified through the achievement of convergence. As a hazard reduction design methodology, the procedure employs a design ground motion rather than recorded motion, but the method retains the displacement-based flavor of all the earlier predictive and design methods. Different from any of the prior methods, however, Division 95 sets forth an explicit rigorous iterative procedure for conducting the complementary linear and nonlinear analyses, as well as a standard for determining when convergence between the two has been achieved.

The prescribed procedure and convergence standard both underscore that the methodology upon which Division 95 is founded is quintessentially a displacement-based iterative method. The procedure requires that the linear elastic dynamic analyses employ effective stiffnesses for the elements or system, obtained from a nonlinear force-displacement analysis and calculated as the secant stiffness of the elements or system *at the calculated peak displacement*. Thus, at the initiation of a Division 95 analysis a set of effective stiffnesses may be assumed, but because the effective stiffness of the structure is explicitly recognized to be displacement dependent, stiffness must be re-calculated whenever the displacements predicted by the dynamic analyses differ from the displacements upon which the assumed effective stiffnesses are based. The re-calculated stiffnesses invoke another iteration of the dynamic analysis unless certain conditions are met. Division 95 explicitly calls for iterations to continue until closure is obtained, with closure defined as a difference of 10 percent or less between the effective stiffness used in the analysis and that re-calculated.

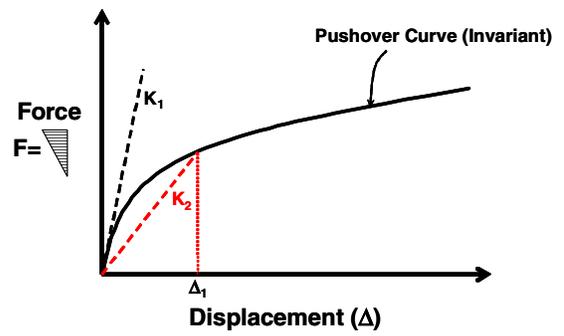
The process by which the effective stiffnesses are computed and implemented in the iterative methodology can be graphically described (Figures 3a through 3g).



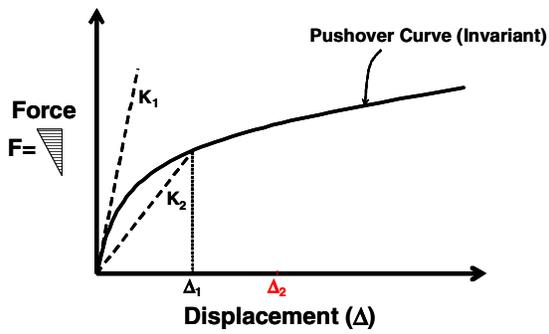
(a)



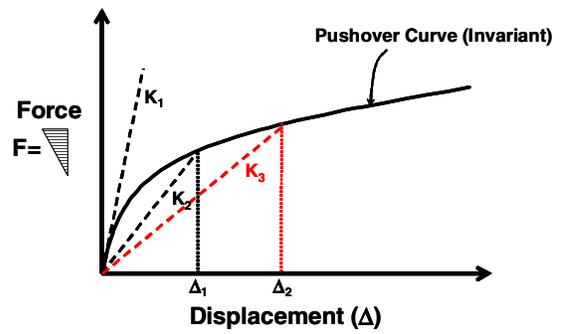
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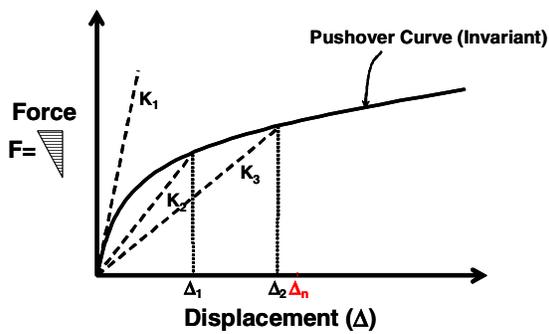
(c)



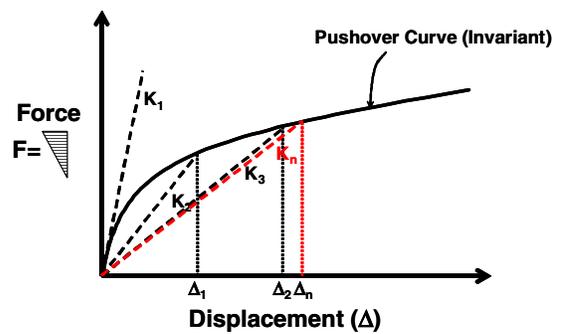
(d)



(e)



(f)



(g)

Figure 3a-g. Schematic of the Secant Stiffness Method.

On the right hand side of Figure 3a is depicted a pushover curve which represents the nonlinear analysis component of the Secant Method. The method allows for this curve to be developed for the structure as a whole, or for multiple curves to be developed for the sub-assemblies and elements of which the structure is composed. Though the pushover curve is referenced during each iteration to identify and update the effective stiffnesses to be included in the linear dynamic analysis of the entire structure (iconographically depicted to the left in the Figure 3a), the curve itself is invariant, meaning that it only need be computed once throughout the course of the analysis. In Figure 3b, an initiating value of the effective stiffness for the first iteration is depicted, here as the elastic stiffness, K_1 . Though Division 95 does not explicitly require this as the starting point, use of the elastic stiffness is recommended by the authors lest the initial assumptions overstep the correct convergence displacements. In Figures 3b-3g, the dynamic analysis icon has been omitted to avoid repetition, but the procedure requires the dynamic analysis to be repeated at each step in the iterations.

In the first iteration, the linear dynamic analysis is performed using K_1 as the input value for the effective stiffness and the resulting displacement, Δ_1 , is output (Figure 3b). An updated effective stiffness, K_2 , is then obtained by entering the nonlinear pushover curve at Δ_1 , as graphically identified in Figure 3c. K_1 and K_2 are then compared, and if the difference between K_1 and K_2 is less than 10%, the analysis is considered to have converged. If the difference between K_1 and K_2 is greater than 10% however, a second iteration which employs K_2 as the effective stiffness is required. A second iteration, identical to the first iteration except that it uses K_2 as the input value for effective stiffness, is depicted in Figure 3d, along with the resulting displacement from that dynamic analysis, Δ_2 . Δ_2 is associated with another updated effective stiffness, K_3 , as shown in Figure 3e. As for iteration 1, the updated effective stiffness is compared with the prior stiffness to determine if the tolerance limits, and thus the convergence criteria, have been satisfied. According to the Division 95 methodology, iterations are to continue until convergence occurs.

An example of a final iteration cycle is shown in Figures 3f and 3g. Figure 3f shows the displacement, Δ_n , output by the n th dynamic analysis, and Figure 3g shows the associated updated effective stiffness, K_n , determined by entering the invariant pushover curve at Δ_n . The figures show that K_n is very similar to K_3 , (K_n is compared with K_{n-1} and in this illustration, $n-1=3$) understood to be within 10% of each other, thus indicating closure of the analysis. Practically speaking, closure could also have been determined by directly comparing Δ_n and Δ_3 as well.

Other references

Further description of the Secant Method is available in other documents such as ATC-40 [3], FEMA 274 [13], FEMA 306 [14] and FEMA 307 [15]. In each of these, the method is described in essentially the same manner as in Division 95 except that in ATC-40 and FEMA 274 the method is set forth as a procedure for evaluating the seismic adequacy of existing buildings in a future design event; and, in FEMA 306 and FEMA 307, it is set forth as a tool for evaluating the performance of earthquake damaged buildings. The procedure for implementing the method however is essentially the same in each of the documents.

APPLICATION

It is obvious that application of the secant method to complex multi-story multi-degree-of-freedom systems would be extremely unwieldy if meaningful detailed information about the behavior of the system during an earthquake is to be generated. Analysis of large buildings commonly entails modeling hundreds, if not thousands of elements, and thousands, if not tens of thousands of degrees of freedom. In these cases, even under optimal circumstances, conducting the extensive nonlinear analysis required in order to

estimate system degradation is daunting. Further, iterating to convergence using inefficient, indirect iteration algorithms is also a formidable task when thousands of parameters are subject to change in each iteration. Worse yet, buildings oftentimes display vertical stiffness or mass non-uniformities that render the use of ‘equivalent’ first-mode approximations inappropriate, effectively eliminating a primary tool from the engineer’s analytical toolbox. Just as commonly, structural systems often exhibit torsional modes of behavior that ought not to be ignored because of their potential to influence both load distribution and failure sequence, which also removes two-dimensional approximations from the analytical toolbox. Thus, a need for a reliable and accurate means of condensing the variables in a complex structure to a manageable number is present. Further, a need for an efficient iteration scheme that can handle a substantial number of variables – sufficient to preserve key characteristic behaviors such as torsional and higher mode response – and that can quickly converge is clear.

Recently, the authors have successfully employed the Secant Method to study the performance of several very large buildings in recent earthquakes, and have employed efficient iteration schemes while rigorously conforming to the analytical requirements of the Secant Method as described in the references provided. One of the buildings studied and the techniques used to study it are described below.

Building Description

The subject building is a 7-story plus basement building with a complete three-dimensional steel frame designed to support all gravity loads. The frame also provides lateral stability in one direction by means of rigid connections. The building’s lateral force resisting system consists primarily of perimeter shearwalls with a minimum thickness of ten inches that encase and are integrated with the steel framing; horizontal wall reinforcing passes through holes in the steel columns where they fall within the wall thickness and light tie reinforcing surrounds the columns at all pilasters. Some of the shearwalls are perforated by regularly sized and spaced window openings and thus consist predominantly of a pier and spandrel configuration. Others are mostly solid infill with relatively sparse intermittent openings and a single stack of openings. Construction of the building was completed in 1960 and as was typical of the era, no special details or concrete mixes were incorporated into the design to mitigate or accommodate cracking due to restraint to shrinkage. The perimeter concrete walls are clad with a four inch thick assembly of glazed and ribbed terra cotta blocks, adhered with pea gravel concrete; mechanically connected with tie wire and pencil rods; and, keyed into the exterior concrete wall surface. The building consists of three architecturally contiguous structurally independent wings – of similar construction but varying configuration and height – which are separated by five inch wide movement joints. Two views of the three-dimensional structure of one of the wings, as modeled using SAP2000NL [16], are provided in Figure 4. The model visually reveals significant potential torsional, mass and stiffness irregularities as the structure steps back with increasing height.

Linear Dynamic Analysis Model

The computer model was developed with the goal of preserving characteristics that were suspected on the basis of conceptual studies and preliminary analysis to have the potential to influence the behavior of the structure in the nonlinear range. Modeling simplifications that might be commonplace in a design context were avoided wherever possible since the goal of the analysis was to generate a detailed prediction of past earthquake response, though such avoidance resulted in a model of cumbersome size for iterative analysis. For example, the model explicitly included nonlinear springs to model uplift at the foundation; elements to model the local thickening of walls at encased columns and beams; and, elements to account for differences between the elevations of slab and beam centerlines. Table 1 summarizes key statistics of the model. While not visible in Figure 4, the model also accounted for the influence of the terra cotta and grout cladding.

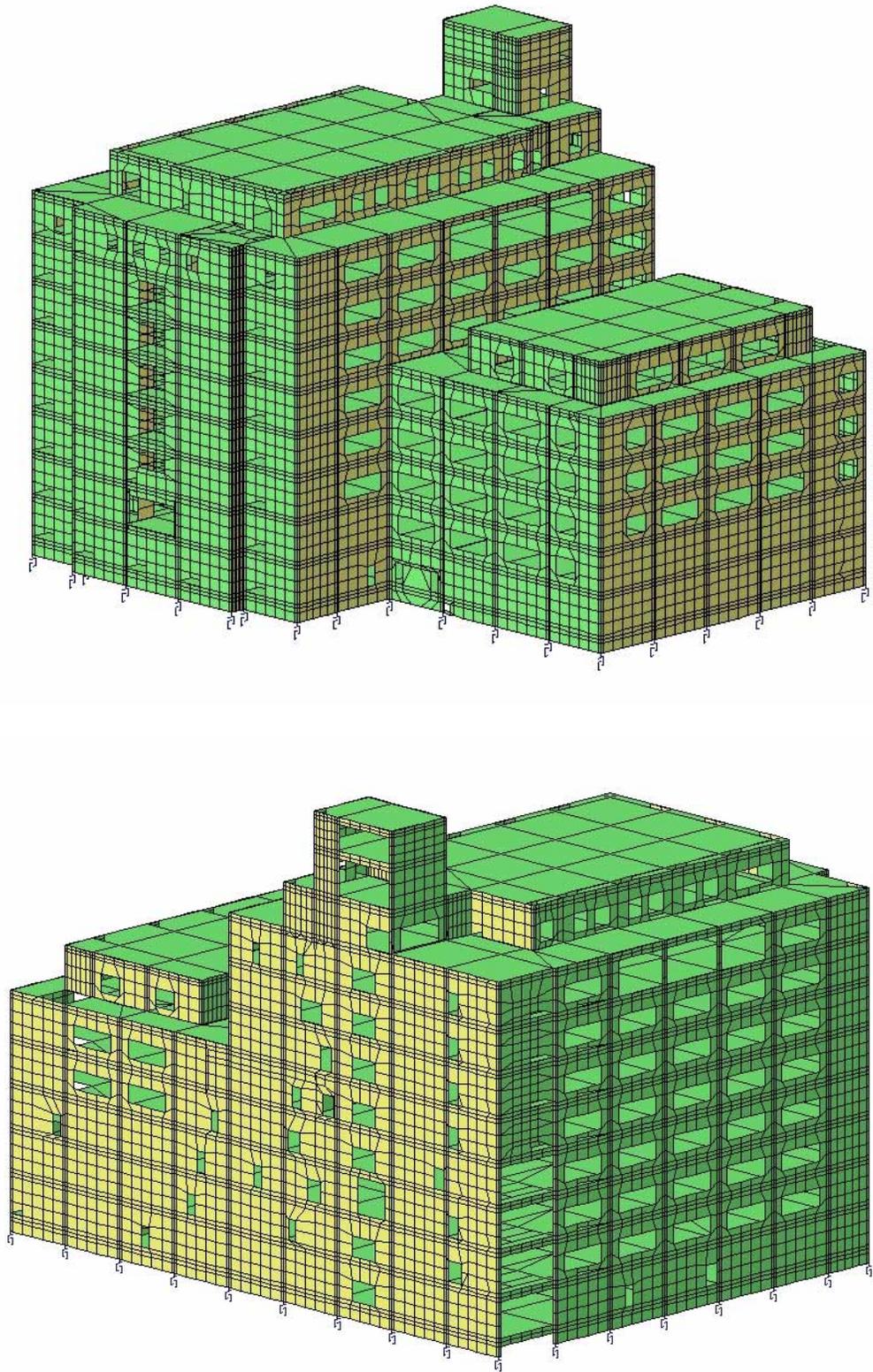


Figure 4. Views of the 7-story plus basement subject building.

Table 1. Key statistics of the computer model of the subject building.

No. of Joints	12,778
No. of Frame Elements	5,878
No. of Shell Elements	11,961
No. of Degrees of Freedom	76,478

Nonlinear Analysis

Nonlinear pushover analysis was selected as the means for defining the force-displacement relationship of the walls in the building under lateral load. These analyses were performed using ANACAP-U [17] and DIANA [18], proprietary nonlinear analysis software, with ANACAP-U employed as the primary analytical engine and DIANA used to confirm the validity of some of the ANACAP-U output and components of the iteration scheme. The ANACAP-U analyses were conducted by the providers of the software. The nonlinear pushover studies were performed on complete perimeter walls, which were the smallest subassemblies subjected to pushovers. All physical features of the walls described in the structural drawings were modeled in the respective software environments, including the steel framing, reinforcing steel, concrete, terra cotta and grout. Two of the ANACAP-U models used are shown in Figures 5a and 5b, one reflecting a wall composed predominantly of piers and spandrels and the other a more solid configuration, respectively.

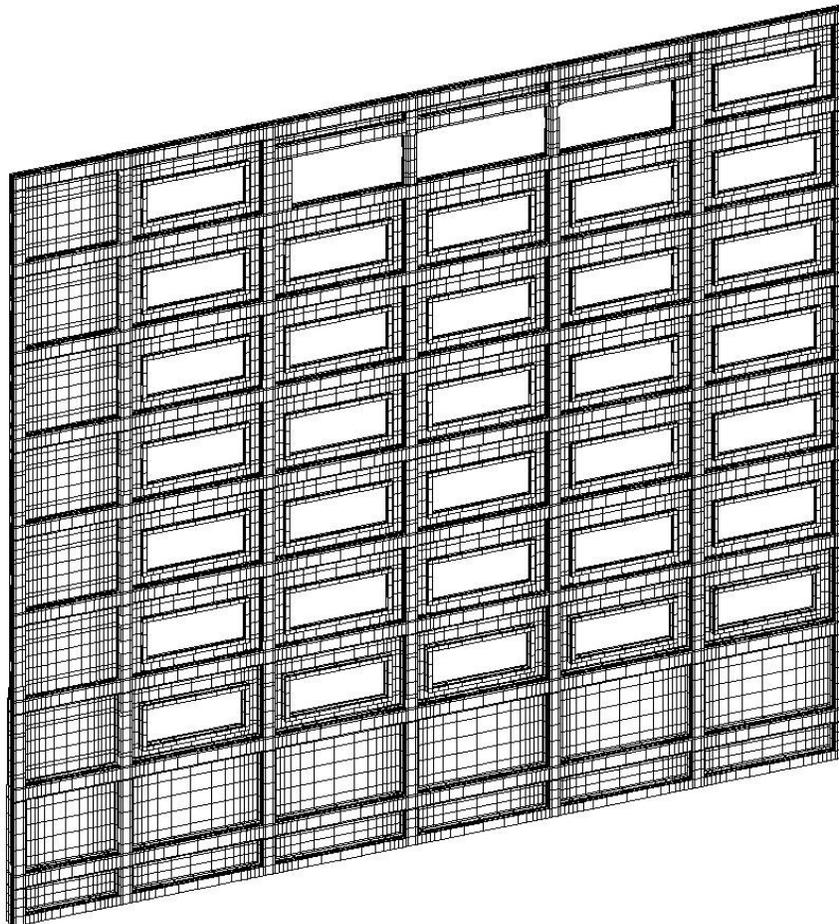
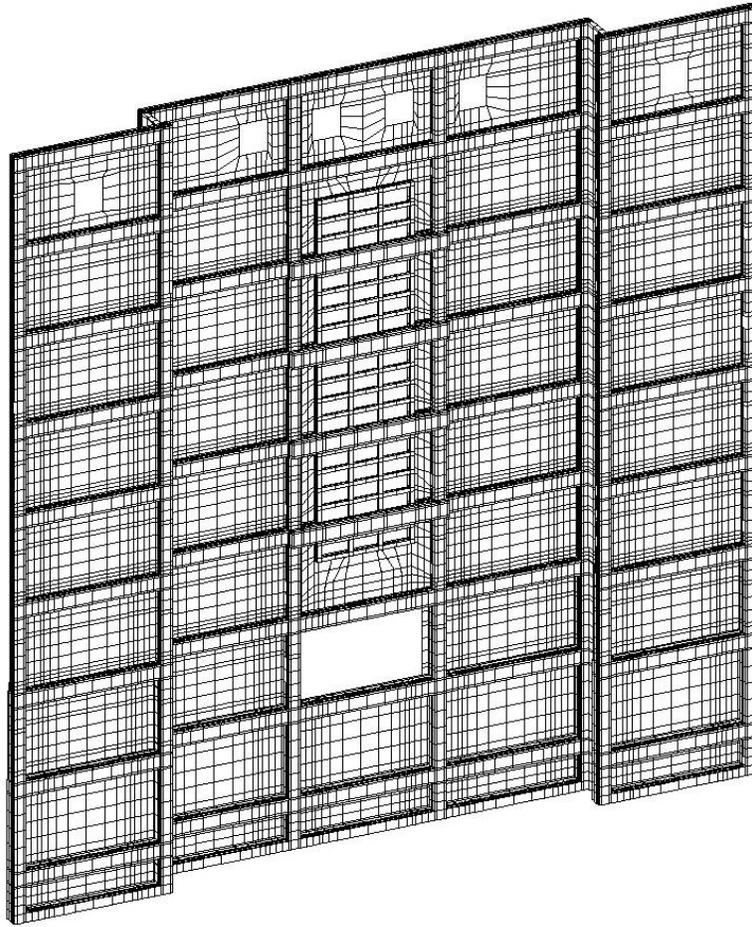


Figure 5a. ANACAP-U computer model mesh for the pier-and-spandrel type prototypical wall.



(b)

Figure 5b. ANACAP-U computer model mesh for the mostly solid type prototypical wall.

Nonlinear studies in both software environments were also conducted of portions of shearwalls to quantify the softening expected due to concrete shrinkage effects, to describe the crack patterns expected prior to the application of lateral forces, and to study the behavior of shrinkage cracks as the walls racked under lateral load. Each of the shearwall sub-models was first subjected to time-dependent shrinkage analyses using a range of relationships that described the time-dependent properties of concrete from the day of casting, including compression strength, f'_c , modulus of elasticity, E , and cracking strain, ϵ_r . These studies resulted in the prediction of generalized crack patterns associated with restraint to shrinkage and defined the initial conditions of the walls for some of the subsequent pushover studies.

For each of the walls several pushover curves were developed, all based upon an incremented normalized triangular loading distribution. Pushovers of bare walls were performed, with and without shrinkage cracking, to provide a baseline against which to compare the predictions for other conditions. Both software environments were also used to study the contribution of the terra cotta cladding assembly to the stiffness of the walls throughout the range of their expected displacements and to study the development and propagation of cracking in the cladding. All these factors were ultimately included in the iterative Secant Method analyses to which the structure was subjected and all figured into the estimates of damage and prediction of cracking caused by the earthquakes.

Secant Method Analysis

With the very large size of the linear and nonlinear models, capturing higher mode response and torsional response effects and correctly predicting locations and patterns of earthquake caused cracking dictated that the mathematical iterations include appropriate idealizations and be conducted in a convergence-efficient manner. Some of the key procedures used are described herein.

Capturing higher mode response

In its simplest form and in a design context, the Secant Method is often implemented with the assumption that building behavior can be adequately described as a single degree of freedom system and thus by relying on its fundamental mode characteristics that allow one step conversion between roof displacement and acceleration and first mode spectral values. This assumption is widely recognized as adequate for generating reasonable estimates of roof displacement because roof displacements are typically dominated by first mode response, even in high rise structures with significant higher mode response. While this assumption also is popular because it greatly reduces the complexity of the iterative process, in an analysis whose goal is to describe the behavior of a complex structure, including earthquake-induced cracking patterns in all stories, such simplifications are not appropriate. In the analysis of the subject building, the authors' desire to preserve the dynamic idiosyncrasies resulting from floor setbacks and wall geometry changes in order to study their influence on cracking patterns demanded a refined iterative algorithm that explicitly accounted for the story-specific deformations and story-specific softening expected from a building of this configuration. To this end, a complete set of story-specific load-displacement relationships were developed for each of the walls modeled by converting each full wall pushover curve into families of curves, including story shear versus story displacement (Figure 6a) and story shear versus interstory drift (Figure 6b). In performing the iterations in the Secant Method analysis, the interstory drifts output from the dynamic analyses were extracted for each story of each wall and these values were used to update the effective stiffness of each wall. Thus the effective stiffness of each wall could be tracked and updated to reflect the localized interstory drift demands from the dynamic analyses, thus capturing significant aspects of higher mode response.

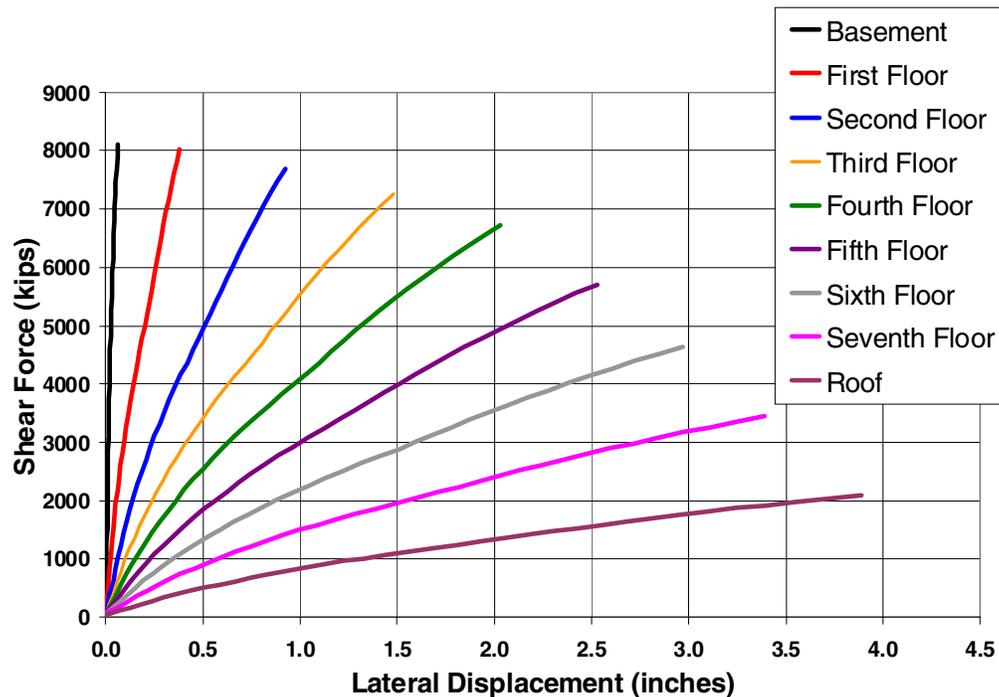


Figure 6a. Story shear-story displacement for the pier-and-spandrel type prototypical wall.

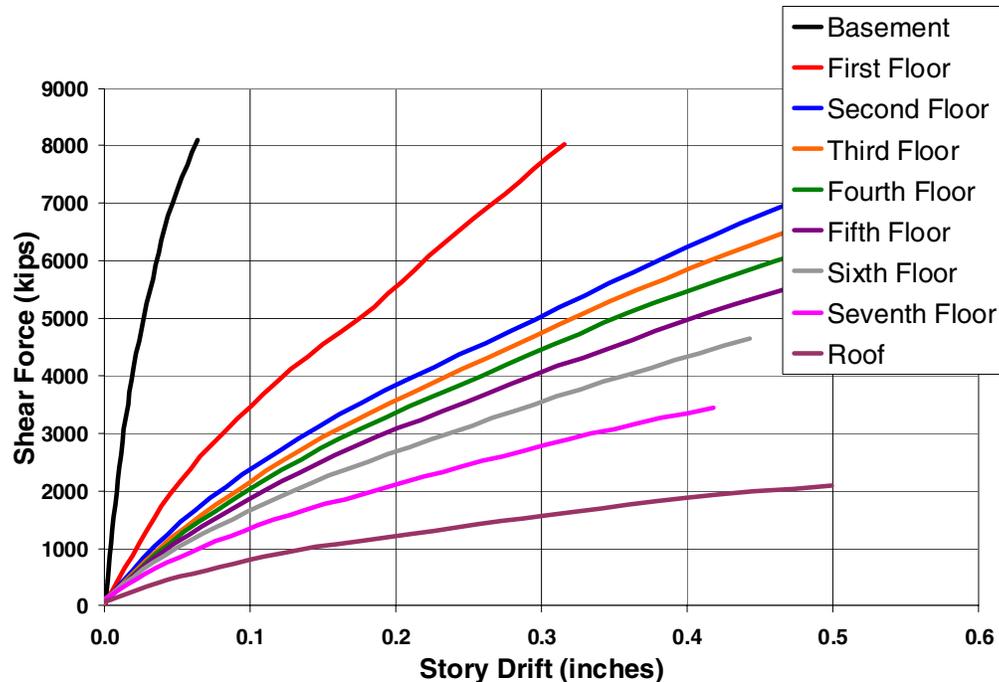


Figure 6b. Story shear-interstory drift curves for the pier-and-spandrel type prototypical wall.

Capturing torsional response

Preservation of the torsional response of the structure was achieved by extending the above-described procedure to all walls in the structure. The torsional response of the building in the linear dynamic environment influenced the interstory drift demands of each story of each wall individually. The iterative algorithm allowed for tracking of the interstory drift demand at each story of each wall and the effective stiffness of each story of each wall was updated independently.

Convergence efficiencies

Enhancement of the mathematical efficiency of the iteration algorithm evolved from the initial ANACAP-U studies of the wall systems shown in Figure 5. The pushover curves for the two wall systems demonstrated, as expected, that the two walls had disparate stiffnesses in their elastic range; however it was also noted that at similar displacements the degree of stiffness degradation (as measured with respect to the initial stiffness) exhibited by each wall was quite similar, despite the obvious differences in the configurations of the wall systems. This observation led to further pushover studies of the majority of the wall systems in the structure using DIANA. The DIANA models were substantially less detailed than the ANACAP-U models but were adequate for quantifying gross characteristics of nonlinear behavior of the walls. Once generated, the DIANA pushover curves for the wall systems that were composed primarily of pier and spandrel modules were compared with each other, as were the pushover curves for the wall systems composed primarily of solid infill modules. Specifically for each group, the relationship between the wall displacements and the percent softening from the initial stiffness was quantified, and in each group wall to wall variations were found to be minimal.

On the basis of these studies it was concluded that with respect to stiffness degradation, the wall systems in this structure that were composed of similar modules behave similarly and that it was not necessary to develop detailed ANACAP-U models for every wall for the purpose of updating their effective stiffnesses in the Secant Method iterations. Instead, recognizing that the initial differences between the various walls

was already explicitly accounted for in the SAP2000NL model, the constancy of the relationship between displacement and stiffness degradation for each prototypical wall type was exploited by simply updating the effective stiffness of each wall system – in terms of percent reduction from their initial condition-- in accordance with the quantified interstory deformation/stiffness reduction relationships for the applicable prototypical wall type. In this manner, the nonlinear modeling effort was vastly reduced without sacrificing accuracy of the result. Furthermore, the iteration algorithm employing stiffness reduction proved to be remarkably efficient, in most cases converging on a solution for all stories of all walls in three or four iteration cycles.

Validation of Analyses

The results of the Secant Method analyses were validated in a straightforward manner. First, validation of the predicted global roof displacement was obtained by modal analysis. Validation of the global roof displacement was required to guard against the potential for the time history based Secant Method analyses having achieved a false convergence. A false convergence can be postulated, for example, when the shape of displacement response spectrum for the studied ground motions exhibits large dips in which an iteration algorithm might become entrapped. The displacement response spectra for the motions recorded near the site of the subject building fortunately exhibited no large dips (Figure 7). The displacement response spectra for the earthquake motions analyzed were studied, and the modal periods, mode shapes and participation factors generated using SAP2000NL were employed in conjunction with displacement response spectra. The roof displacements determined from these modal analyses were compared with those predicted by the Secant Method.

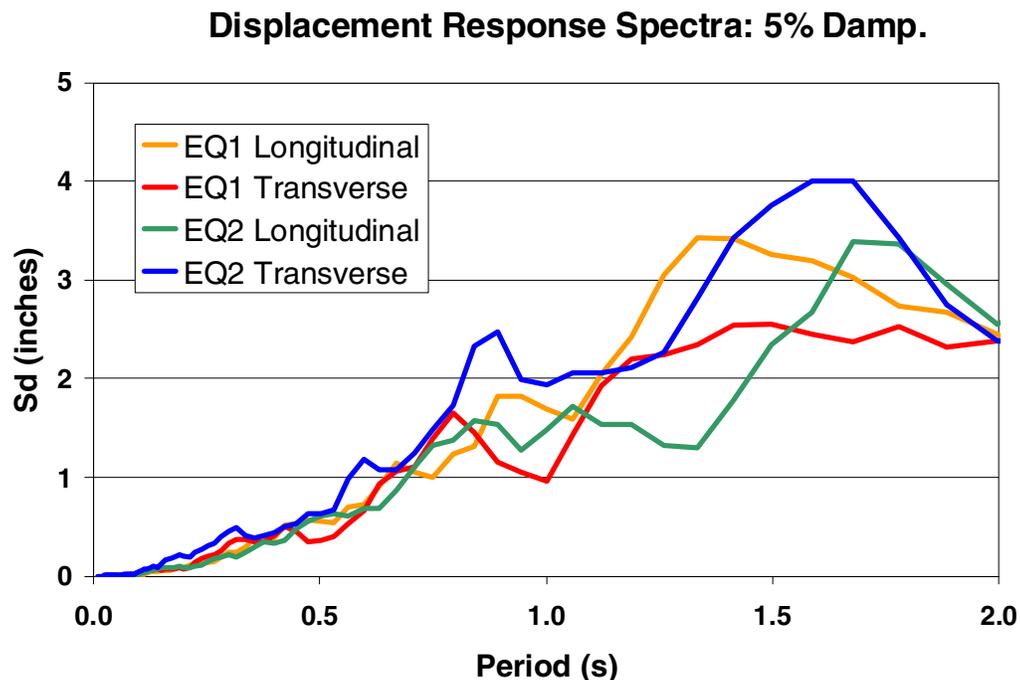


Figure 7. Displacement response spectra of some of the ground motions used in the study.

Validation studies were also undertaken in order to confirm if the generalized predictions of cracking from the analyses could be confirmed in the physical structures. Confirmation was sought both for the cracking in the concrete and the cracking in the terra cotta cladding. Detailed maps of the exposed faces of the

concrete and terra cotta were developed and these were carefully compared to the predictions generated by the analyses. Significant differences between the predictions and the infield conditions could indicate that the Secant Method analyses had converged at the wrong set of displacements. As such, physical confirmation of analytical predictions is highly recommended by the authors.

CONCLUSIONS

The Secant Method can be efficiently applied to large complex buildings in a manner that preserves details of behavior often eliminated during the course of modeling. Higher mode response and torsional response can be captured if warranted.

Because the subject structures were subjected only to low ductility demands, these studies demonstrate only that the Secant Method is applicable to these situations. Even so, the authors recommend that additional validation studies using instrumented structures be conducted to better understand limitations in the use of the method that might exist.

Users of the method should be aware that theoretically the Secant Method tends to overpredict structural displacement since stiffness modifications made in the analyses reflect the predicted peak displacements, which may only occur at one instant during the shaking event. The Secant Method however necessarily assumes that the structure is pre-softened in reflection of the peak displacements even at the initiation of the ground shaking.

The Secant Method as described in Division 95 and in other documents also does not explicitly provide direction with regard to damping. In accordance with Division 95, the studies mentioned in this paper did not include damping modification. The authors believe that due to the low ductility demands on the subject structures, standard assumptions normally employed in elastic analyses as to damping are justified. However, the method has the flexibility to account for other situations, if appropriate.

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