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CONVERGENCE BEHAVIOR OF SUBSTITUTE STRUCTURE METHOD IN MOTEMS

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Abstract

This paper examines the convergence behavior of the Marine Oil Terminal Engineering and Maintenance Standards (MOTEMS) substitute structure method and a secant-stiffness based substitute structure method when implemented in an automated process. It is found that the MOTEMS method does not converge whereas secant-stiffness based method converges when the first estimate of the displacement demand is taken as that of the initial linear-elastic, 5%-damped system. If the initial estimate is sufficiently close to the final solution, the MOTEMS method may also converge. The MOTEMS method, when it converges, leads to a displacement demand similar to that from the secant-stiffness based method. Therefore, the secant-stiffness based substitute structure method may be used in lieu of the current MOTEMS method for structures that are designed according to the MOTEMS requirements.

Keywords: Substitute structure method; Marine oil terminals; MOTEMS; Seismic analysis; Seismic demand

1. Introduction

To help prevent oil spills and to protect public health, safety and the environment, minimum engineering, inspection and maintenance criteria for Marine Oil Terminals (MOTs) are codified in Chapter 31F of the California Building Code (CBC), commonly known as Marine Oil Terminal Engineering and Maintenance Standards (MOTEMS) [1]. The MOTEMS specify an analytical procedure for estimating seismic demands in MOTs.

The current version of MOTEMS specifies a “refined analysis” or substitute structure method to estimate the seismic displacement demand in MOTs. The substitute structure method specified in MOTEMS is an iterative method that aims to estimate the seismic displacement demand in a nonlinear system with a series of linear-elastic systems with an effective period and effective damping ratio. This paper examines the convergence behavior of the MOTEMS method when implemented in an automated process, such as a program written in a computing platform (e.g., MATLAB [2]). This paper also examines the convergence of a secant-stiffness based substitute structure methods specified in the ASCE/COPRI 61-14 standard [3], which is often used by practicing engineers for estimating seismic demand in MOTs, and compares results from the two procedures.

It is found that the MOTEMS method does not converge but the secant-stiffness based method converges when the first estimate of the displacement demand is taken as that of the initial linear-elastic, 5%-damped system. If the initial estimate is sufficiently close to the final solution, the MOTEMS method may converge. The MOTEMS method, when it converges, leads to a displacement demand similar to that from the secant-stiffness based substitute structure method. Therefore, the secant-stiffness based substitute structure method may be used in lieu of the MOTEMS method for structures that are designed according to the MOTEMS requirements.

2. Substitute Structure Methods

The substitute structure analysis approach was originally proposed in the mid-1970s by Sozen and his colleagues [4, 5]. This method was initially presented as a design (and not an analysis) procedure to determine design forces corresponding to a given type and intensity of earthquake motion represented by the design spectrum [5] with the specific objective being to establish minimum strengths of components of the structure so that a tolerable response displacement is not likely to be exceeded. With recognition of the importance of displacements rather than forces in structural design, this method received renewed attention in early-1990s for displacement-based design [6,7,8]. Subsequently, Priestley et al. [9] proposed several versions of the substitute structure method for displacement-based design of bridges. These methods involve replacing the inelastic system with a substitute linear-elastic model with an effective stiffness and an effective damping, while keeping the mass constant, such that the displacement of the original nonlinear system is the same as the displacement of the substitute linear-elastic system. The substitute structure will typically have a period longer than and a damping higher than that of the initial elastic structure (Fig. 1). The following is a description of two variations of the substitute structure method.

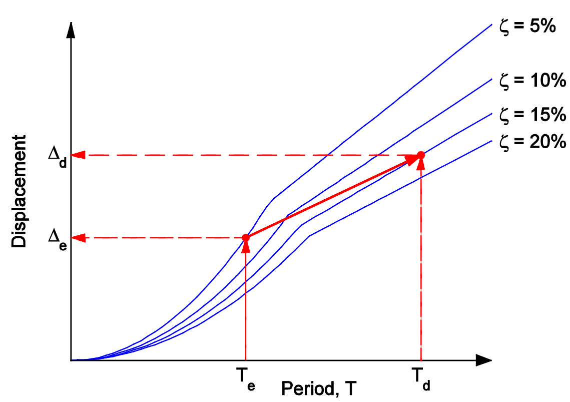

Figure 1. Period elongation and increased damping in the substitute structure method.

2.1 MOTEMS Substitute Structure Method

The substitute structure method adopted in MOTEMS for displacement evaluation of piers and wharves is based on the procedure presented in Chapter 5, Section 5.3.1(c) of Priestley et al. [9]. Following is a step-by-step summary for this method:

1. Idealize the pushover curve from nonlinear pushover analysis (Fig. 2) and estimate the yield force F_y and yield displacement Δ_y.

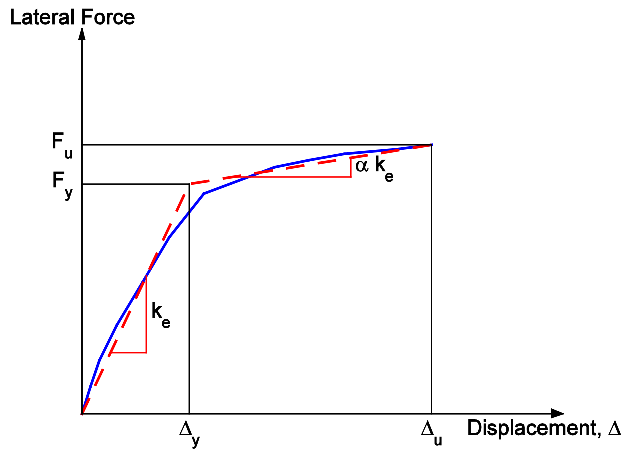

Figure 2. Idealization of nonlinear pushover curve.

2. Compute the effective linear-elastic lateral stiffness, k_e, as the yield force, F_y, divided by the yield displacement, Δ_y.
3. Compute the effective linear-elastic structural period in the direction under consideration from

$$T_e = 2\pi\sqrt{\frac{m}{k_e}} \tag{1}$$

4. Determine the displacement, Δ_d, of the effective linear-elastic system from

$$\Delta_d = S_A \frac{T_e^2}{4\pi^2} \tag{2}$$

where S_A is the 5%-damped spectral acceleration corresponding to the linear-elastic structural period, T_e.

5. Select the initial estimate of the displacement demand in the substitute structure method as

$$\Delta_{d,i} = \Delta_d \tag{3}$$

6. Compute the ductility, $\mu_{\Delta,i}$,

$$\mu_{\Delta,i} = \frac{\Delta_{d,i}}{\Delta_y} \tag{4}$$

7. Use the appropriate relationship between ductility and damping for the component undergoing inelastic deformation to estimate the effective structural damping, $\xi_{eff,i}$. In lieu of more detailed analysis, use the following the relationship for concrete and steel piles connected to the deck through dowels embedded in the concrete.

$$\xi_{eff,i} = 0.05 + \frac{1}{\pi}\left(1 - \frac{1-\alpha}{\sqrt{\mu_{\Delta,i}}} - \alpha\sqrt{\mu_{\Delta,i}}\right) \tag{5}$$

where α is the ratio of second slope over elastic slope. Eq. (5) for effective damping was developed by Kowalsky et al. [7] for the Takeda hysteresis model of systems force-displacement relationship with unloading stiffness, $k_{unloading}$, and the initial elastic stiffness, k_e, related to the ductility, μ, as $k_{unloading} = k_e / \mu^{0.5}$.

8. Generate an acceleration response spectrum for various damping levels. To convert the 5%-damping acceleration response spectrum to a spectrum for a different damping level, use damping adjustment factors specified in MOTEMS [1].
9. From the acceleration response spectra for various damping levels, create displacement spectra using the following relationship between spectral acceleration and spectral displacement (Fig. 3):

$$S_D = \frac{T^2}{4\pi^2} S_A \tag{6}$$

10. Using the curve applicable to the effective structural damping, $\xi_{eff,i}$, find the effective period, $T_{d,i}$, corresponding to estimated displacement demand, $\Delta_{d,i}$ (Fig. 3). Linear interpolation may be used if necessary.

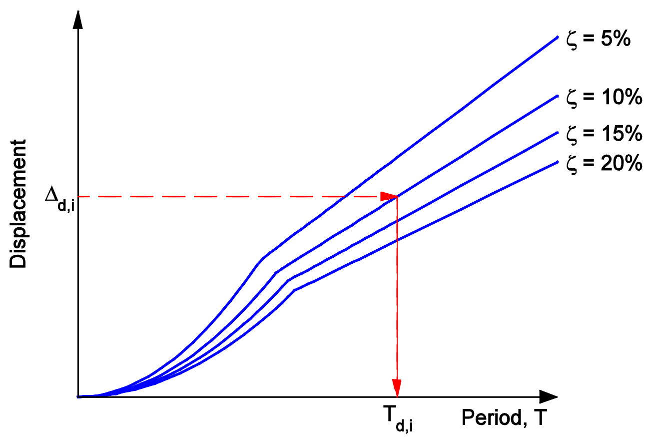

Figure 3. Computation of period from estimated displacement demand and effective damping.

11. Compute the effective stiffness $k_{eff,i}$, from:

$$k_{eff,i} = \frac{4\pi^2}{T_{d,i}^2} m \tag{7}$$

12. Estimate the required strength $F_{d,i}$ from:

$$F_{d,i} = k_{eff,i} \Delta_{d,i} \tag{8}$$

13. Plot the $F_{d,i}$ and $\Delta_{d,i}$ on the force-displacement curve established by the pushover analysis (Fig. 4). Since this is an iterative process, the intersection of $F_{d,i}$ and $\Delta_{d,i}$ most likely will not fall on the force-displacement curve and a second iteration will be required. Estimate the displacement demand for the next iteration, $\Delta_{d,j}$, as the intersection between the force-displacement curve and a line between the origin and $F_{d,i}$ and $\Delta_{d,i}$ (Fig. 4).
14. Repeat steps 6 to 13 with $\Delta_{d,i} = \Delta_{d,j}$ until satisfactory values of force, F_d, and displacement, Δ_d, that lie on the force-deformation curve are obtained (Fig. 4).

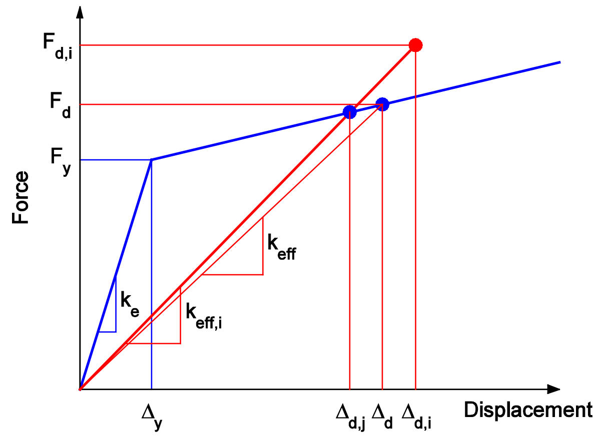

Figure 4. Solution strategy and effective stiffness in the MOTEMS substitute structure method.

2.2 Secant-Stiffness based Substitute Structure Method

Another version of the substitute structure method described in Chapter 4, Section 4.5.2(b) (iii) of Priestley et al. [9] involves using secant stiffness at an estimated displacement to define the substitute linear elastic structure. Following is a step-by-step summary of this secant-stiffness based method:

1. Idealize the pushover curve from nonlinear pushover analysis (Fig. 2) and estimate the yield force F_y and yield displacement Δ_y.
2. Compute the effective linear-elastic lateral stiffness, k_e, as the yield force, F_y, divided by the yield displacement, Δ_y.
3. Compute the effective linear-elastic structural period in the direction under consideration from

$$T_e = 2\pi\sqrt{\frac{m}{k_e}} \tag{9}$$

4. Determine displacement, Δ_d, of the effective linear-elastic system from

$$\Delta_d = S_A \frac{T_e^2}{4\pi^2} \tag{10}$$

   where S_A is the 5%-damped spectral acceleration corresponding to the linear elastic structural period, T_e.
5. Select initial estimate of the displacement demand in the substitute structure method as

$$\Delta_{d,i} = \Delta_d \tag{11}$$

6. Compute the ductility, $\mu_{\Delta,i}$,

$$\mu_{\Delta,i} = \frac{\Delta_{d,i}}{\Delta_y} \tag{12}$$

7. Use the appropriate relationship between ductility and damping for the component undergoing inelastic deformation to estimate the effective structural damping, $\xi_{eff,i}$. In lieu of more detailed analysis, use the following the relationship for concrete and steel piles connected to the deck through dowels embedded in the concrete.

$$\xi_{eff,i} = 0.05 + \frac{1}{\pi}\left(1 - \frac{1-\alpha}{\sqrt{\mu_{\Delta,i}}} - \alpha\sqrt{\mu_{\Delta,i}}\right) \tag{13}$$

where α is ratio of second slope over elastic slope.

8. Compute the force, $F_{d,i}$, on the force-deformation relationship associated with the estimated displacement, $\Delta_{d,i}$ (Fig. 5).
9. Compute the effective stiffness, $k_{eff,i}$, as the secant stiffness from

$$k_{eff,i} = \frac{F_{d,i}}{\Delta_{d,i}} \tag{14}$$

10. Compute the effective period, $T_{eff,i}$, from

$$T_{eff,i} = 2\pi\sqrt{\frac{m}{k_{eff,i}}} \tag{15}$$

11. For the effective structural period, $T_{eff,i}$, and the effective structural damping, $\xi_{eff,i}$, compute the spectral acceleration $S_A(T_{eff,i}\xi_{eff,i})$ from the design acceleration response spectra for various damping levels.
12. Compute the new estimate of the displacement, $\Delta_{d,j}$, from:

$$\Delta_{d,j} = \frac{T_{eff,i}{}^{2}}{4\pi^2} S_A(T_{eff,i}, \zeta_{eff,i}) \tag{16}$$

13. Repeat steps 6 to 12 with $\Delta_{d,i} = \Delta_{d,j}$ until displacement, $\Delta_{d,j}$, computed in step 12 is sufficiently close to the starting displacement $\Delta_{d,i}$, in step 6 (Fig. 5).

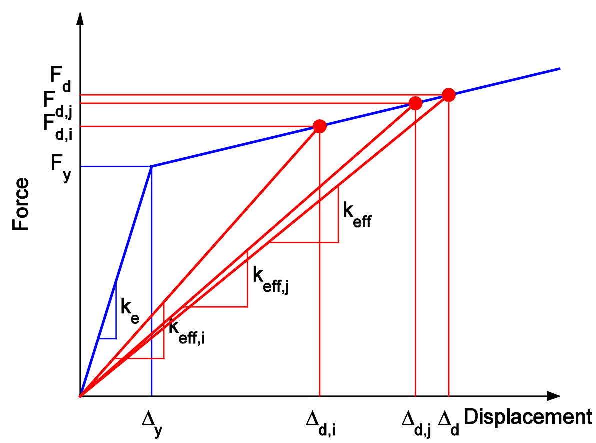

Figure 5. Solution strategy and effective stiffness in secant-stiffness based substitute structure method.

3. Convergence Behavior of Substitute Structure Methods

Convergence behavior of the two substitute structures methods as described in the preceding section are examined in this section with the aid of an example. The example structure considered is an idealized structure with an initial-elastic vibration period equal to 0.5 sec, its yield strength equal to one-fourth of the strength required for it to remain linearly elastic for a selected earthquake design spectrum (Fig. 6), 5% damping for linear-elastic behavior, and a bi-linear force deformation behavior with post-yield stiffness equal to 5% of the initial elastic stiffness (Fig. 7).

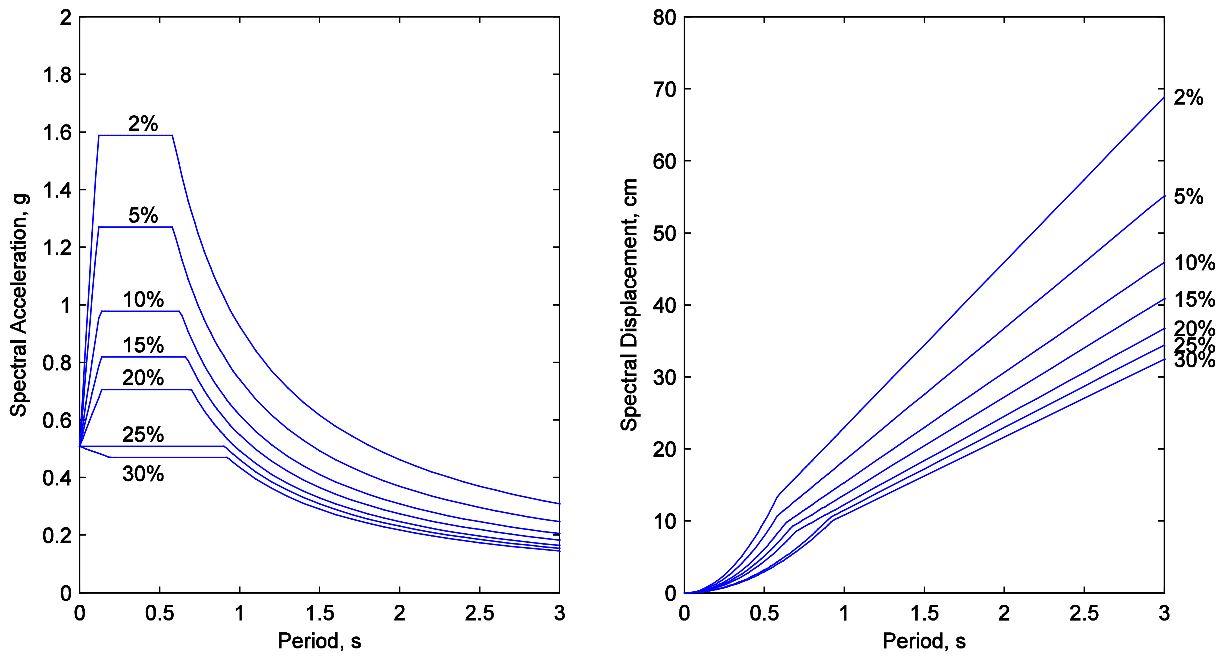

Figure 6. Earthquake design spectrum selected for convergence evaluation of substitute structure methods.

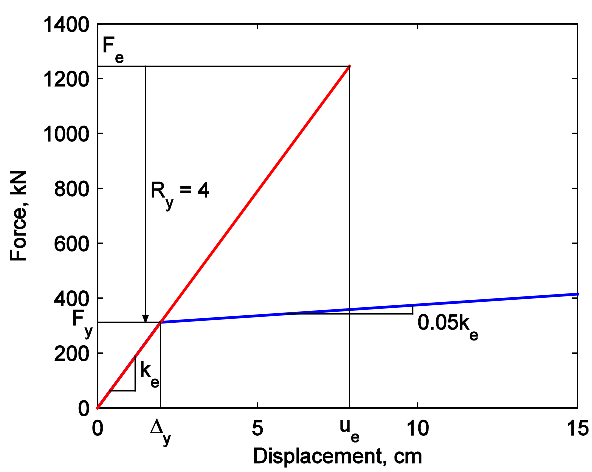

Figure 7. Force-deformation properties of the selected example structure.

3.1 Convergence Behavior of MOTEMS Substitute Structure Method

Fig. 8 summarizes the implementation of the MOTEMS substitute structure method. The initial estimate of the displacement demand is obtained from the 5%-damped linear elastic spectrum for a system with a 0.5 sec period. This estimate of $\Delta_{d,1} = 7.88$ cm is used to compute the ductility demand from Eq. (4) which in turn is used to compute the effective damping $\zeta_{eff,1} = 18.5\%$ from Eq. (5). The effective period, $T_{d,1} = 0.655$ sec is read-off from the 18.5%-damped displacement spectrum for $\Delta_{d,1} = 7.88$ cm (Fig. 8a). The effective period $T_{d,1} = 0.655$ sec is then used to compute the effective stiffness of $k_{eff,1} = 91.9$ kN/cm from Eq. (7). Using Eq. (8), the estimated strength equals $F_{d,1} = 724.4$ kN for a system with $k_{eff,1} = 91.9$ kN/cm and $\Delta_{d,1} = 7.88$ cm. When the

$F_{d,1}$ and $\Delta_{d,1}$ curve is plotted on the force-displacement curve, the intersection of these curves does not fall on the force-displacement curve (Fig. 8b). The next iteration assumes the displacement demand as the intersection between the force-displacement curve and a line between the origin and $F_{d,1}$ and $\Delta_{d,1}$, which in this case is $\Delta_{d,2} = 3.52$ cm (Fig. 8b). The second iteration with $\Delta_{d,2} = 3.52$ cm leads to $\zeta_{eff,2} = 12.1\%$, $T_{d,2} = 0.394$ sec, $k_{eff,2} = 254$ kN/cm, and $F_{d,2} = 893.8$ kN. However the $F_{d,2}$ and $\Delta_{d,2}$ curve does not intersect the force-deformation relationship of the selected example (Fig. 8b) and as a result the automated procedure cannot proceed any further. In other words, the procedure, as applied, fails to converge.

It is useful to note that the new estimate in the first iteration is going to be smaller than the first estimate (i.e., the displacement of the 5%-damped linear elastic system) and hence the solution moves to the left side of the force-deformation curve (Fig. 8b). Eventually, this trend will end up moving sufficiently to the left so that the force-deformation relationship does not intersect with the $F_{d,i}$ and $\Delta_{d,i}$ curve. While the results in Fig. 8 are presented for a selected example, similar non-convergence was found to consistently occur for systems with a range of periods and strengths. This implies that the MOTEMS substitute structure method, when automated using the first estimate of the displacement demand as equal to that of the displacement of the initial linear elastic system, and subsequently using the next estimate as the displacement at the intersection of the force-deformation and $F_{d,i}$ $\Delta_{d,i}$ curves, does not converge. This observation, however, does not preclude convergence if the displacement estimate was guessed to be very close to (or equal) to the final convergence, as will be demonstrated later in this paper.

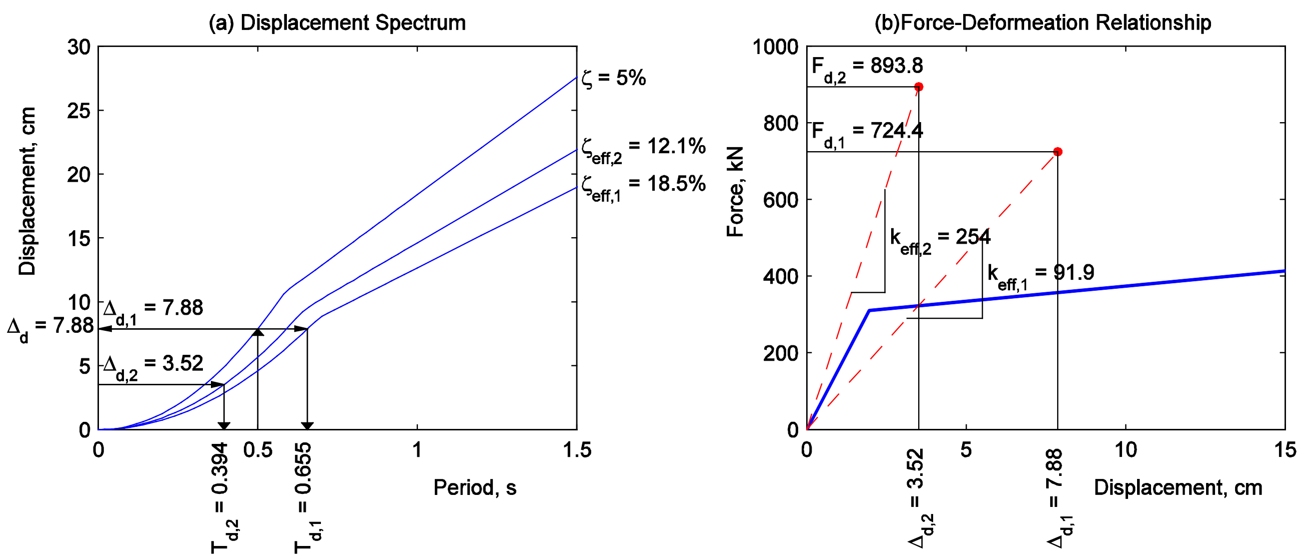

Figure 8. Convergence behavior of an example structure for MOTEMS substitute structure method.

3.2 Convergence Behavior of Secant-Stiffness based Substitute Structure Method

Fig. 9 summarizes the implementation of the secat-stiffness based substitute structure method. The initial estimate of the displacement demand is obtained from the 5%-damped linear elastic spectrum for a system with a 0.5 sec period. This estimate of $\Delta_{d,1} = 7.88$ cm (Fig. 9a) is used to compute ductility from Eq. 12 which in turn is used to compute effective damping $\zeta_{eff,1} = 18.5\%$ from Eq. (13). The force corresponding to the displacement of $\Delta_{d,1} = 7.88$ cm is estimated from the force-deformation relationship to be $F_{d,1} = 357.8$ kN which is used to compute the effective (or secant) stiffness from Eq. (14) of $k_{eff,1} = 45.4$ kN/cm (Fig. 9b). Using Eq. (15) gives $T_{eff,1} = 0.933$ sec. The estimate of the displacement demand of a substitute structure is then computed from a linear elastic spectrum for 18.5% damping and 0.933 sec as $\Delta_{d,2} = 11.8$ cm (Fig. 9a). Since this new estimate of displacement $\Delta_{d,2} = 11.8$ cm is not close to the intial estimate of $\Delta_{d,1} = 7.88$ cm, the process is repeated with $\Delta_{d,2} = 11.8$ cm. The procedure converges after the 6th cycle with the final displacement $\Delta_d = \Delta_d = 14.1$ cm. It is useful to note that the convergence criteria used in this analysis was specified so that the difference between the displacement demands from two successive iterations was no more than 1%. Although the procedure converged after six iterations, Fig. 9 includes results only from first two iteration and the last iteration for clarity. While the results in Fig. 9 are presented for a selected example, similar convergence was found to consistently occur for systems with a range of periods and strengths.

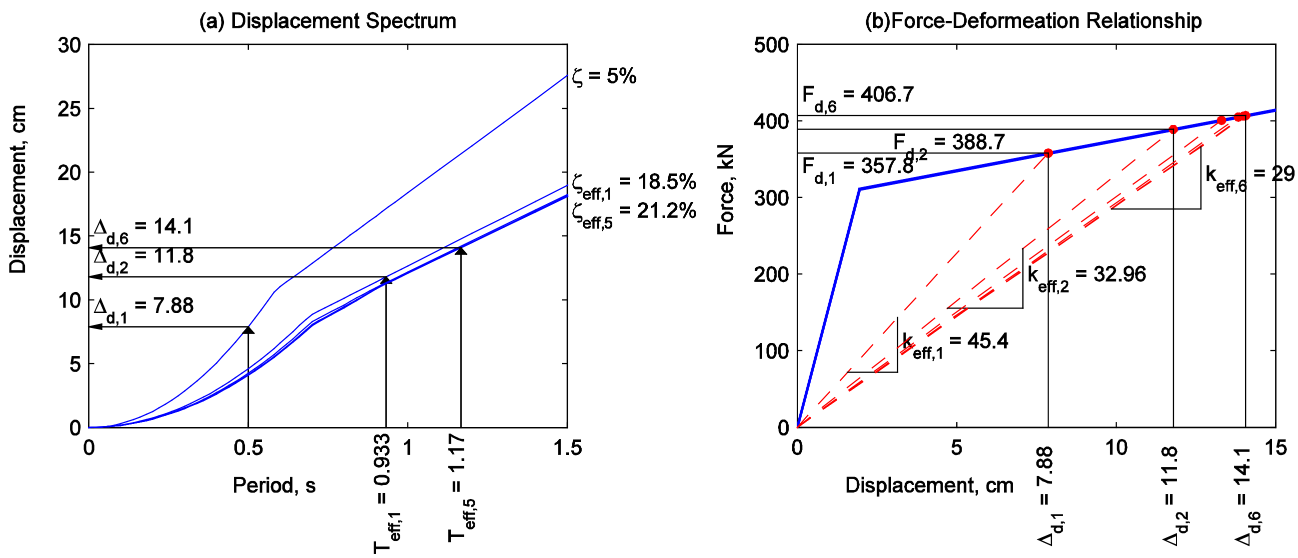

Figure 9. Convergence behavior of an example structure for secant-stiffness based substitute structure method.

3.3 Equivalence between MOTEMS and Secant-Stiffness based Substitute Structure Methods

The preceding sections demonstrated that the MOTEMS method does not converge while the secant-stiffness based method converges when the first estimate of the displacement demand is taken as that of the initial linear elastic 5%-damped system. It has been noted that practicing engineers use the secant-stiffness based substitute structure method even for structures that are designed for the MOTEMS requirements. Therefore, it is useful to check if the two methods give the same displacement demand if an initial estimate in the MOTEMS method was to be selected to force convergence. For this purpose, the MOTEMS method is implemented with an initial estimate of the displacement demand to be equal to the final displacement demand from the secant-stiffness based substitute structure method.

The results presented in Fig. 10 show that the MOTEMS method not only converges but also gives the same displacement demand as that of the secant-stiffness based substitute structure method. This implies that convergence issues noted in the MOTEMS substitute structure method, as currently described in the MOTEMS document, are due to selection of the initial displacement estimate. If the initial estimate is sufficiently close to the final solution, the MOTEMS method may converge. More importantly, the MOTEMS method, when it converges, leads to a displacement demand similar to that from the secant-stiffness based substitute structure method.

Since it is not always possible to guess the displacement estimate to be very close to the final displacement demand, the aforementioned discussion indicates that the current version of the MOTEMS method may not be readily automated due to the lack of robust convergence behavior. However, the secant-stiffness based substitute structure method is robust-enough and converges. More importantly, the MOTEMS method and the secant-stiffness based substitute structure method leads to essentially identical results when the former method converges. Therefore, the secant-stiffness based substitute structure method may be used in lieu of the MOTEMS method for structures that are designed according to the MOTEMS requirements.

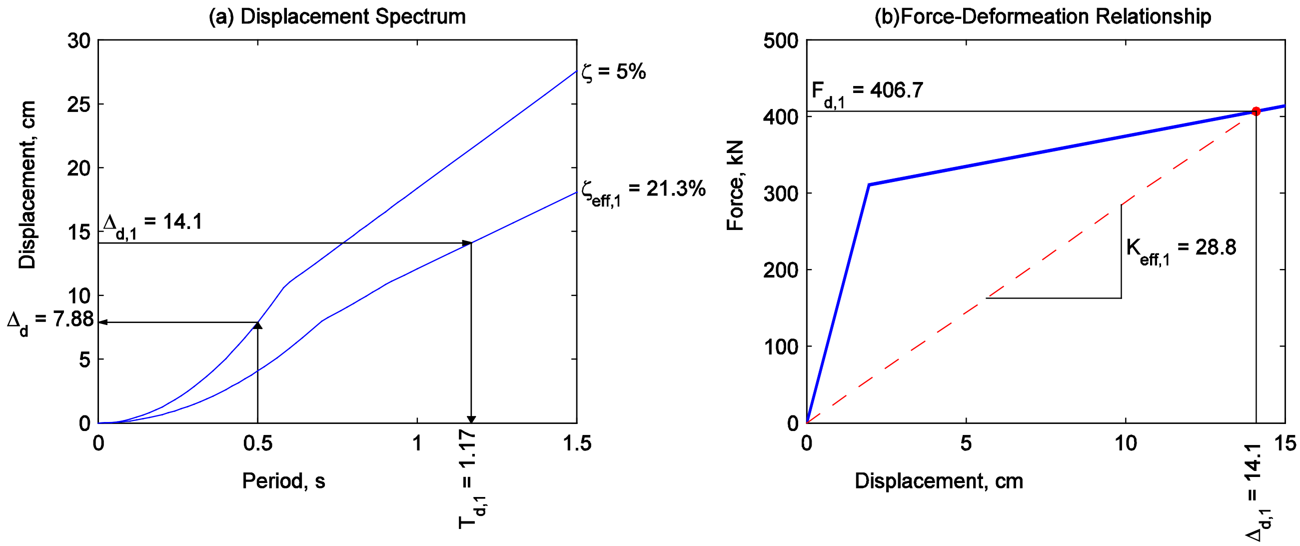

Figure 10. Convergence of an example structure for MOTEMS substitute structure method with initial estimate of the displacement selected to be equal to the final displacement from the secant-stiffness based substitute structure method.

4. Conclusions

This paper examined the convergence of the MOTEMS method and a secant-stiffness based substitute structure method when implemented in an automated process. It is found that the MOTEMS method does not converge whereas the secant-stiffness based method converges when the first estimate of the displacement demand is taken as that of the initial linear elastic 5%-damped system. If the initial estimate is sufficiently close to the final solution, the MOTEMS method may converge. More importantly, the MOTEMS method, when it converges, leads to a displacement demand similar to that from the secant-stiffness based substitute structure method. Therefore, the secant-stiffness based substitute structure method may be used in lieu of the MOTEMS method for structures that are designed according to the MOTEMS requirements.

5. Acknowledgements

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6. References

[1] MOTEMS (2010): Marine Oil Terminal Engineering and Maintenance Standards, Title 24, California Code of Regulations, Part 2, California Building Code, Chapter 31F (Marine Oil Terminals). California State Lands Commission.

[2] MATLAB (2014): MATLAB Release 2014a, The Mathworks, Inc., Natick, MA.

[3] American Society of Civil Engineers (2014): "Seismic Design of Piers and Wharves," ASCE Standard ASCE/COPRI 61-14.

[4] Gulkan, P. and Sozen, M.A. (1974): "Inelastic Response of Reinforced Concrete Structures to Earthquake Motions," ACI Journal, 71(12): 604-610.

[5] Shibata, A. and Sozen, M.A. (1976): "Substitute-Structure Method for Seismic Design in R/C," Journal of the Structural Division, ASCE, 102(ST1): 1-17.

[6] Calvi, M.C. and Kingsley, G.R. (1994): "Displacement Based Seismic Design of Multi-Degre-of-Freedom Bridge Structures," Proceedings of 2nd International Workshop on the Seismic Design of Bridges, Queenstown, New Zealand, August.

[7] Kowalsky, M.J., Priestley, M.J.N, MacRae, G.A. (1994): "Displacement-Based Design – A Methodology for Seismic Design Applied to Single Degree of Freedom Reinforced Concrete Structures," Report No. SSRP – 94/16, University of California, San Diego.

[8] Kowalsky, M.J., Priestley, M.J.N, MacRae, G.A. (1994): "Displacement-Based Design of RC Bridge Columns," Proceedings of 2nd International Workshop on the Seismic Design of Bridges, Queenstown, New Zealand, August.

[9] Priestley, M.J.N., Sieble, F., Calvi, G.M. (1996): "Seismic Design and Retrofit of Bridges," John Wiley & Sons, Inc., New York, USA.