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Sensitivity of Flexibility Monitoring of Offshore Jacket Platforms

Flexibility monitoring is a vibration-based method for simplifying the detection of major underwater damage on offshore jacket platforms. Ambient vibrations are detected at each of the underwater framing levels relative to abovewater vibration in the fundamental sway and torsional modes. Derived are flexibility parameters which relate to the shear flexibilities of each framing bay and of the foundation. Great promise has been shown by laboratory and field testing. This paper presents a comprehensive sensitivity assessment for severance of diagonal members over a wide range of structural redundancy for generic platform configurations.

Introduction

The inspection of offshore jacket platforms for underwater structural damage can be time consuming, difficult, costly, and sometimes hazardous. In an attempt to achieve a simpler technique for detection of major damage, abovewater-placed accelerometers have been utilized to detect ambient (wave and wind) excited random vibrations. To be extracted were the resonant frequencies of lower beam modes of the platform [1, 2]. The idea was that damage major enough to cause significant loss of structural integrity (typically severance of diagonal face members or loss of pile foundation support) would produce detectable frequency shifts. Unfortunately, two factors led to weakness of this approach [3]. The first was unacceptably low sensitivity for deepwater structures, which are characterized by a high degree of structural redundancy. The second was an inability to discriminate frequency shifts due to mass changes, most notably due to ever changing levels of production liquids in storage tanks on the platform decks. Still another drawback of the approach was the poor capability to identify the location of damage as an aid to further diagnostic actions. Consequently, this approach, called "global vibration monitoring," has not proven to be a generally viable one.

In support of the Mineral Management Service of the Department of the Interior, a new vibration technique called Flexibility Monitoring was conceived. (The activity was part of a research program for offshore minerals operations aimed at ensuring protection of life, health, and the natural environment.) It avoids these basic difficulties at the expense of complication in implemenation. The source of the complication is the need to place accelerometers at underwater positions on corners of the jacket at the various framing levels. This has been demonstrated to be quite practical when a platform has been outfitted with suitable instrument chutes attached to corner legs. Operating from abovewater, instrument packages can then be slid down the chutes to any desired level and remotely clamped in place. Processing of the ambient vibration data of suitably positioned accelerometers yields "flexibility parameters" for each jacket framing bay. These parameters closely relate to the fundamental shear flexibility in each of the three directions – namely, in the broadside and endon lateral directions and in torsion about the vertical axis. The foundation of the platform can be similarly characterized.

Flexibility monitoring has shown considerable promise in a series of laboratory and field tests [4–6]. The laboratory tests were part of government-prescribed testing of a subscale, simplified platform model to evaluate alternative vibration-based inspection techniques, each to be applied by a selected investigator [7]. Each investigator was given access to the model to obtain baseline data and to formulate at test plan. With the investigators out of contact, these planes were implemented by the government for four damage scenarios. After receipt of this specified test data, each investigtor was expected to assess the scenarios relative to likelihood of damage, degree of structural degradation, and location of damage. A major consequence of this program was the identification of Flexibility Monitoring as a highly promising technique, worthy of further evaluation.

The next step was additional laboratory testing on the same subscale model, directed toward sensitivity evaluations and checkout of portable data analysis equipment in anticipation of field testing. Subsequently, field experiments were conducted on two deepwater platforms in the Gulf of Mexico that had been provisioned with instrument chutes and associated instrument packages and data acquisition systems. The totality of the laboratory and field testing has shown that Flexibility Monitoring has the potential for effective and practical implementation. The practicality of implementing the method in the field, from both opreational and data accuracy standpoints, was clearly shown by the favorable experience on the Chevron Garden Banks platform [6]. As a further contribution to evaluation of the Flexibility Monitoring approach, this paper presents analytically derived sensitivity behavior for severance of primary diagonal members over a wide range of platform redundancy.

Generic Platform Models

In previous studies [3, 4] the generic behavior of fixed off-

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shore platforms has been utilized to describe the dynamic characteristics of such structures and to gain perspectives on sensitivity to local structural failures. The present investigation was aimed at extending the generic shear beam model to include: 1) out-of-plane coupling due to eccentric deck mass and member failures, 2) effects of distributed jacket structural mass and submerged member apparent fluid mass, and 3) effects of foundation flexibility. Sensitivity of the fundamental lateral and torsional modes to member severance in the presence of the above effects was evaluated. The purpose of this analytical investigation was to establish trends in behavior rather than authentic simulations.

The present generic model configuration is schematically illustrated in Fig. 1. A displacement coordinate system referenced along the geometric center of each level is noted in that figure.Cross-sectional dimensions are uniform over the entire structural height (i.e., no leg batter). Individual bays, including the abovewater section, are all of the same height. The deck is configured as a rigid plate which is uniformly distributed over the surface area, plus an eccentric concentrated mass.

Consistent with observed behavior of detailed finite-element platform models and supported by field data comparisons, the jacket structure is assumed to deform as a shear beam. For simplicity, a number of assumptions consistent with such behavior were made: 1) main legs and horizontal braces are axially rigid; 2) lateral elastic structural stiffness of all bays at and below the water line is completely due to axial stiffness of the diagonal braces (i.e., bending stiffness of the main legs was negligible in comparison); and 3) lateral elastic structural stiffness of the abovewater bay is due to bending stiffness of the main legs. An additional simplifying assumption employed in simulation of foundation flexibility is that the foundation level deformed as a rigid plate. Thus, foundation stiffness is described in terms of uncoupled stiffness coefficients associated with the three translational and three rotational displacements. As a result of the jacket structure assumption, the vertical motions and out-of-plane rotational motions of all levels above the foundation level are equal to the respective foundation motions. The displacements required to describe the independent motion of any level above that of the foundation are thus the two sways x and y and torsion θ_z (see Fig. 1). In the case of the 5-bay configuration illustrated in Fig. 1, the number of the structural degrees of freedom is therefore 6 for the foundation, plus 6 levels at 3 degrees of freedom each, totalling 24. In the case of a rigid foundation, there were a total of 18 dof.

The jacket structure mass and apparent fluid mass associated with submerged structure are accounted for by equal allocation to the main legs. Due to the kinematic assumptions, moments of inertia associated with structural mass of the distributed legs act in all three rotational degrees of freedom. Apparent mass for surrounding water is effective for motion perpendicular to the axis of each leg and is given by the mass of water displaced. In addition, since the main legs are typically flooded, the mass of entrained water is included.

Three generic configurations with contrasting levels of complexity are chosen for damage sensitivity study. They consist of a 4-leg, 4-bay structure much like the one employed in reference [4], an 8-leg, 6-bay structure of similar complexity to SP-62C studied in reference [3], and a 12-leg, 11-bay structure with bay complexity resembling that of the lower sections of the Shell Cognac platform [6]. The jacket, deck, and foundation properties of each configuration are given in reference [6]. In each case, the x and y-sway motions are uncoupled, both elastically and inertially. Figure 2 presents the geometry and the x-sway mode shapes for both rigid and flexible foundation conditions. Table 1 summarizes characteristics of the fundamental modes. Each platform configuration is designated by the number of legs, followed by R or F to denote a rigid or flexible foundation, respectively. For example, the configuration $4R$ in Table 1 refers to the 4-leg platform on a rigid foundation. Included are the natural frequencies of the fundamental sway and torsion modes, the fractional contribution of the deck to total modal kinetic energy (K.E.), and the fractional contribution of foundation to the total modal potential energy (P.E.). Clearly for the 4-leg con-

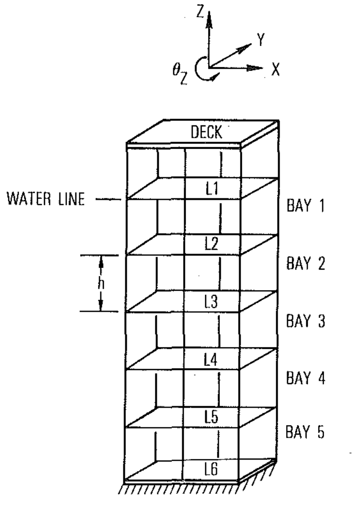


Fig. 1 Five-bay generic model schematic

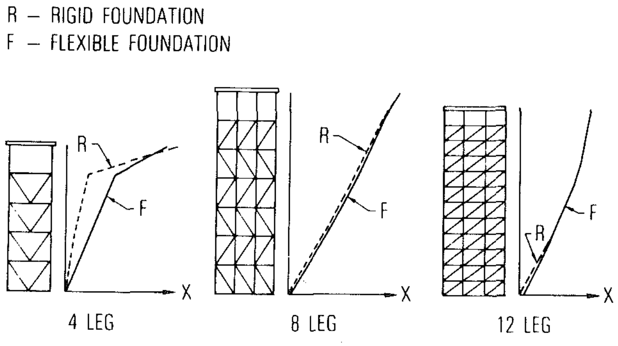


Fig. 2 Geometric and X-sway mode shapes

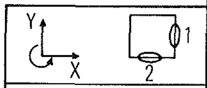
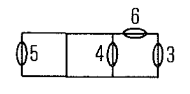
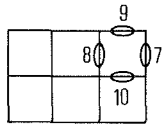
Table 1 Modal characteristics of generic platform models

Configuration Legs/Foundation	Natural frequencies (Hz) x-sway	y-sway	torsion	Deck K.E. (percent)	Foundation P.E. (percent)
$4R^{(a)}$	1.46	1.45	2.18	$85^{(b)}$	0
$4F$	1.07	1.07	2.09	72	49(x and y)
$8R$	0.49	0.49	0.62	63	0
$8F$	0.33	0.40	0.60	63	54(y), 35(x)
$12R$	0.25	0.25	0.27	26	0
$12F$	0.24	0.24	0.26	25	8(y), 7(x)

(a) Foundation: $R\sim$rigid, $F\sim$flexible

(b) Values of deck kinetic energy apply to both x and y-sway directions

Table 2 Summary of frequency shifts due to single diagonal severance

	FAILURE CASE	PERCENT FREQUENCY REDUCTION*		
		X SWAY	Y. SWAY	TORSION
	1	—	4.9-7.5 (2.7-5.0)	1.7-4.8 (2.1-5.5)
	2	4.6-7.0 (2.5-4.8)	—	2.2-9.4 (2.2-6.4)
	3	—	3.1-8.2 (1.0-3.3)	1.0-4.2 (1.5-6.6)
	4	—	1.4-3.7 (0.6-1.8)	0.0-0.2 (0.0-0.3)
	5	—	1.4-4.9 (0.9-2.4)	1.8-8.2 (1.4-8.2)
	6	0.8-2.2 (0.5-1.3)	—	0.0-0.6 (0.2-0.7)
	7	—	0.0-2.0 (0.0-2.1)	0.0-0.8 (0.0-0.8)
	8	—	0.0-1.2 (0.0-1.3)	0.0 (0.0)
	9	0.0-1.2 (0.0-1.3)	—	0.0-0.4 (0.0-0.4)
	10	0.0-0.8 (0.0-0.8)	—	0.0 (0.0)

*NUMBERS NOT IN PARENTHESES DENOTE RIGID FOUNDATION.
NUMBERS IN PARENTHESES DENOTE FLEXIBLE FOUNDATION.

figuration, the deck mass (rather than the jacket structural and apparent fluid masses) plays the major role in determination of modal frequency. Moreover, the relatively uniform slope of submerged jacket modal displacements for the 4-leg configuration indicates that the fundamental lateral modes are governed by quasi-static behavior of the jacket. In contrast, the 12-leg configuration behaves more like a shear beam with uniform mass and stiffness distribution as indicated by the relatively low contribution of deck mass to modal kinetic energy and by the near quarter-wave shape of the lateral mode shape.

Sensitivity to Diagonal Severance

The three platform models are subjected to severance of single diagonals on various vertical faces and in various bays to assess sensitivity of fundamental lateral mode parameters.

A summary of frequency shifts due to identified diagonal severance is presented in Table 2. The range of frequency reduction results from variation with damaged bay level. In all cases, the highest frequency sensitivity occurs for damage in the lowest bay, with sensitivity monotonically decreasing with distance above the foundation. This sensitivity chracteristic arises as a result of the contribution of jacket structural mass and apparent fluid mass; that is, the highest fraction of system mass is affected by damage at the lowest bay level. As noted in prior work (reference [3]), the general trends indicate that frequency sensitivity decreases with increasing bay redundancy and effective number of bays. (The effective number of bays is the number of underwater bays which would yield the same deck deflection per unit force as would the actual platform, considering foundation and abovewater flexibilities.) The extreme case is the 12-leg one where frequency change due to any one diagonal severance on the lowest bay falls to less than 0.05 percent. In general, frequency sensitivity is an unreliable inidicator of structural failure in view of the potential for foundation flexibility and deck mass changes to produce frequency changes of similar degree.

The parameter which is most sensitive to diagonal failures (namely, the bay flexibility parameter) has been discussed previously [4]. The bay flexibility parameter, C, is defined as the ratio of relative average lateral or torsional deflection across that bay to the corresponding lateral or torsional deflection for the abovewater bay: namely, for the x direction and the ith bay (see Fig. 1)

$$C_{xi}=\frac{\bar{x}_i-\bar{x}_{i+1}}{\bar{x}_D-\bar{x}_1} \qquad (1)$$

where the overbar denotes the average deflection and the subscript refers to the bay number or deck (D). Typical flexibility sensitivities for the three representative platforms are presented in Fig. 3. As noted in reference [4], foundation rotational flexibility produces an overall shift in flexibility parameters due to added rigid-body angular displacement of the jacket. This effect is most pronounced in the 4-leg platform, but becomes negligible for the 12-leg platform. Contributions of jacket and fluid mass lead to a monotonically decreasing value of the flexibility parameter with distance above the foundation, especially pronounced for the 12-leg configuration. In all platform configurations, the presence of diagonal. The absolute increase in the damaged-bay flexibility parameter is relatively insensitive to foundation flexibility. On the other hand, the fractional change in the flexibility parameter generally decreases with increasing foundation flexibility due to the increase in its nominal value. This effect is strongest for the 4-leg configuration.

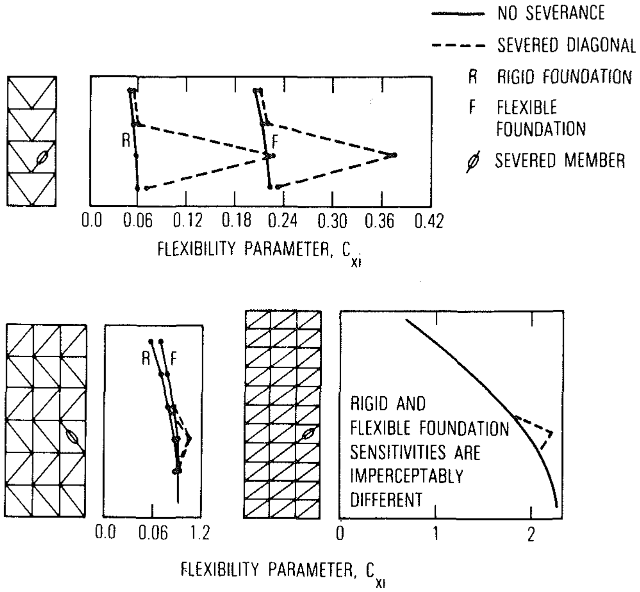


Fig. 3 Typical flexibility sensitivities of platforms

A complete list of flexibility parameter sensitivities appears in Appendix B of reference [6].

Perspective on Damage Sensitivity

The importance of field detection of any structural damage increases with the degree of associated structural integrity degradation. A simple indicator of such degradation is the damaged strength rating, DSR [8]

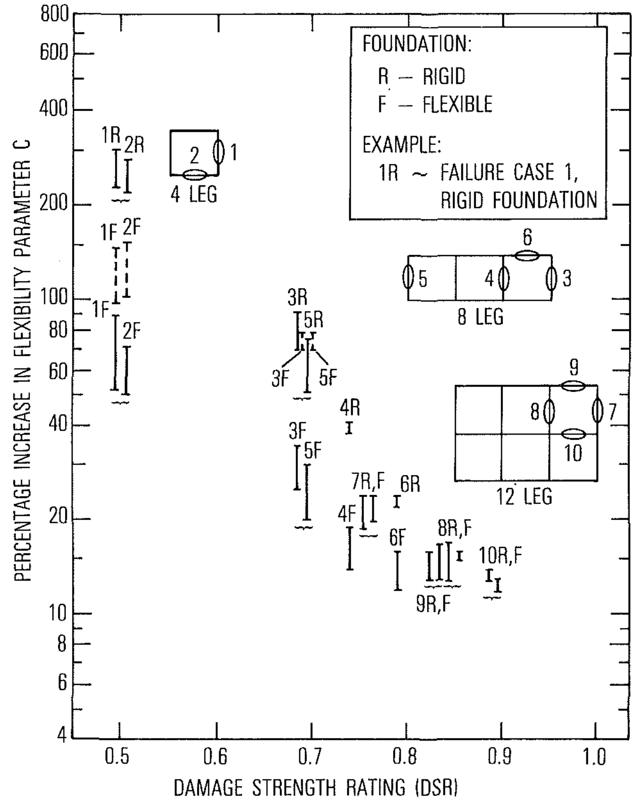


Fig. 4 Flexibility parameter versus damage strength rating (single diagonal severance)

$$\mathrm{DSR} = \frac{\text{damaged strength}}{\text{intact strength}} \tag{2}$$

As used in reference [3] and here, this rating is based upon the *greatest increase* in diagonal member loading resulting from a failure, considering constant static lateral shear force to act across the bay containing the failed member(s) and linear elastic structural behavior

$$\mathrm{DSR} = \frac{\text{member loading for intact structure}}{\text{member loading for damaged structure}} \tag{3}$$

A rough estimation of the damaged strength rating is obtained as follows: Given a bay which carries a transmitted shear force F shared by N diagonals, the individual diagonal member forces are proportional to F/N. If M members have failed, the redistributed individual member loads are $F/(N-M)$, neglecting nonuniform distribution of loading due to eccentric positioning of the damage. Thus

$$\mathrm{DSR} = \frac{F/N}{F/(N-M)}$$

$$= \frac{N=M}{N} = \frac{\text{number of intact diagonals}}{\text{original number of diagonals}} \tag{4}$$

A more accurate measure of DSR is based upon linear static analysis of a damaged bay, considering redistribution of member loads due to unsymmetric damage (leading to coupled lateral and torsional shear deflection across the bay). A bay flexibility parameter, which is determined from the shape of a fundamental mode, also is influenced by the effects of mass distribution to changes in the distribution of bay shear forces. Figure 4 displays the percentage increase in flexibility parameter (based upon mode shapes), as a function of the damage strength rating, for single diagonal severance. Schematics of the failure cases are shown for ready reference. The vertical lines denote the range of values for severance in the various bays; in all cases, the trend is to higher percentage change with greater depth of the bay. The dotted lines denote values from the torsion mode and appear only for the flexible foundation case when they exceed the values from the sway mode. Cases 3 and 5 yield different results only because of mass asymmetry on the deck.

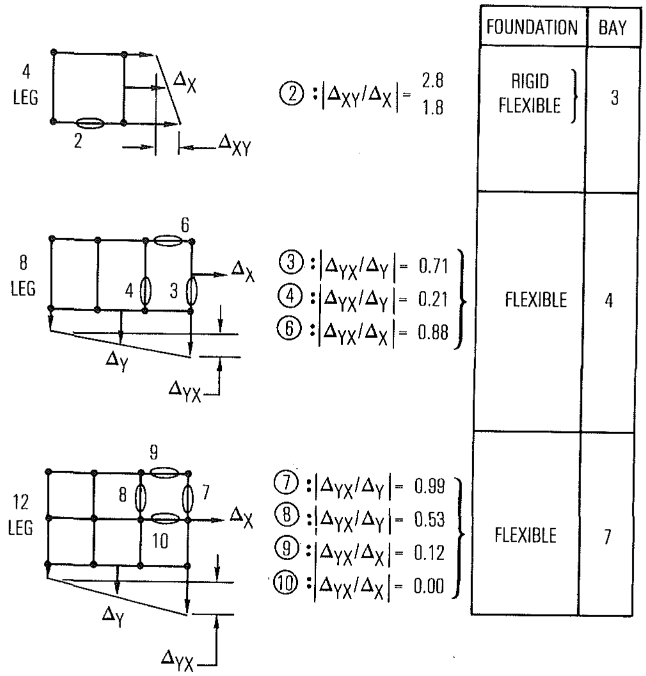


Fig. 5 Examples of employment of lateral-torsional coupling to locate failure face

Figure 4 shows the expected decreasing trend in flexibility parameters change with increased damage strength rating. The relatively low redundancy of a 4-leg platform (with single diagonal brace) leads to flexibility parameter changes which are from 100 to 300 percent in at least one of the affected modes. It is expected that crossed bracing would reduce the sensitivity to severance of one vertical diagonal to no more than 50 to 150 percent. For results of a study of a particular X-braced, 4-leg platform, see reference [9]. For the 8-leg platform, the sensitivity to loss of diagonal stiffness depends a great deal on the face involved. On the exterior endon faces, the flexibility parameter change is a relatively high 50 to 90 percent, with the torsion mode being a far stronger indicator for the soft foundation. For the interior endon and the broadside faces, the lateral mode is the most responsive with the change as low as 12 percent. The flexible foundation is not significant relative to the platform flexibility for the 12-leg platform; the changes for failure on any face do not fall below the least sensitive 8-leg platform failure case with a flexible foundation, namely, 12 percent.

As seen in Fig. 3, the bay and orientation of a severed diagonal are clearly identifiable from the changes in flexibility parameter for the sway modes. The potential for identification of the particular face in which damage occurs is assessed by noting the difference in flexibility readings at bay corners rather than the overall lateral flexibility parameter based upon average bay deflections. Typical failure cases for each representative structure, illustrated in Fig. 5, indicate that localization to a face is possible when the failed member is a major contributor to bay torsional stiffenss. (The failure case numbers correspond to those in Fig. 4.)

Summary and Conclusions

The sensitivity of the Flexibility Monitoring method for damage detection is explored using generic mathematical models spanning a wide range of geometric complexity. Observed trends are:

(*a*) A vertical diagonal member failure produces a change in flexibility parameter only for the bay and in the direction or directions involved (that is, one sway and possibly torsion). Elsewhere the changes were negligible.

(*b*) A foundation flexibility change produces a smoothly varying shift in the overall flexibility parameter shape. (The same is true for deck mass change.[1]) The strongest effect is due to change in the rotational flexibility about a sway axis, which produces platform rigid-body rocking.

(*c*) A vertical diagonal member failure sometimes introduces sufficient torsion/sway coupling so as to permit identification of the face on which the failure has occurred.

It is therefore concluded that Flexibility Monitoring has the necessary discriminatory attributes to enable feasible detection of vertical diagonal severances. The method can localize the damage to the bay and direction involved (and possibly even to the face), and it will not be misled by foundation and deck mass changes.

In ascending order of significance, the percentage shift of flexibility parameters due to vertical diagonal severance increases with the following factors:

(*a*) the depth of the bay;
(*b*) the degree of lateral/torsion coupling produced by the severance;
(*c*) the lack of significant rocking flexibility of the foundation;
(*d*) the reduction of redundancy of vertical diagonals within a bay.

The reader is cautioned that the numerical values of sensitivity from this study are only rough indicators of sensitivities expected for actual platforms. The trends in sensitivity, however, are believed to be reliable.

Based upon the analytical studies and extrapolating therefrom, the following judgments about the capability of flexibility monitoring are made on the premise that at least a 15 to 20-percent local increase in a bay or foundation flexibility parameter will be necessary for reliable failure identification in field situations [6].

(*a*) For a 4-leg platform, there is little question of adequacy to identify severance of a single vertical diagonal brace even if cross braced.

(*b*) For an 8-leg platform, such identification is possible for a relatively stiff foundation in rocking, especially in the absence of cross bracing. Cross bracing and significant rocking make the identification of individual vertical diagonal severances problematic, especially for interior and broadside face members.

(*c*) Identification of single severance of most vertical diagonals in a 12-leg jacket is problematic. Severance of endon outerface vertical diagonals is expected to be identifiable if uncrossed.

Multiple member damage in a given bay, affecting the same sway direction, produces larger flexibility parameter increases than that for failure of a single diagonal, and identification becomes increasingly easier. It appears that an effect comparable to two diagonal severances will be identifiable in most cases for either the 8-leg platform on a soft foundation or the 12-leg platform. More definitive statements will require analytical predictions of sensitivity for specific structural configurations.

In concept, Flexibility Monitoring is directed towards the detection of shear flexibility change of individual bays of a jacket and of the foundation. As such, it has strong capability for detecting severance of vertical diagonal members, which are the principal contributors to jacket shear flexibility. In general, horizontal members do not contribute significantly to this flexibility and, thus, their failure is generally not detectable by this method. To the extent that failure of vertical members or piles induces significant rotation in mode shapes, or induces an increase in lateral flexibility of the foundation, such failures will show up in flexibility parameters [5 and 9]. Specific attention has not been given to such failures in this study.

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[1] Observed in experimental results (Sec. 2, reference [6]) and expected on intuitive grounds.

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