Categorizing Component Failure in Offshore Platforms

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Abstract: A significant part of reliability-based design is determining the importance of a member in a structure to the behavior of the entire structure. Such an evaluation is necessary for many of the load and resistance factor design (LRFD) formats that have been proposed. After its importance is known, the member can be categorized rationally so that similar members in a structure can be designed to similar standards. One measure of member importance is the change in behavior of the remaining structure when a member fails. A computationally efficient reanalysis algorithm and classification procedure is necessary when determining the significance of a member to a structure so the cost of design does not become exorbitant. A reanalysis algorithm and a proposed classification system for members in jacket-type offshore platforms are presented in this paper.

Introduction

A necessary part of reliability-based design is evaluating the consequences in a structure caused by the failure of a component within the structure. Members having similar failure consequences can be grouped together and designed to similar standards. One measure of a member's failure consequences is the change in the forces in other members. Another is the serviceability of the remaining structure. These changes in behavior can be determined by removing a single member from the structure and computing the changes in the forces and the displacements in the remaining structure. This member then can be replaced and another member can be removed; the process is repeated for all members in the structure. Failure, in the context of this paper, is defined as the complete loss of a member's resistance to load; this would be the critical case. Such failures can occur as the result of fatigue, poor construction, excessive load, or mechanical damage.

Jacket-type offshore platforms (Fig. 1) are composed of many members. Graff (1981) presents typical platform configurations. The cost of design would become excessive if a complete analysis was performed each time a member was removed from the structure. A computationally efficient procedure has been developed for use in member categorization and is presented in this paper. This algorithm is based upon the initial strain concept of structural reanalysis. Advantage was taken of the fact that the degrees-of-freedom (DOF) to be modified for the evaluation of the failure consequences of a member are known; they are only the DOF associated with the member being removed. The time required for reanalysis using

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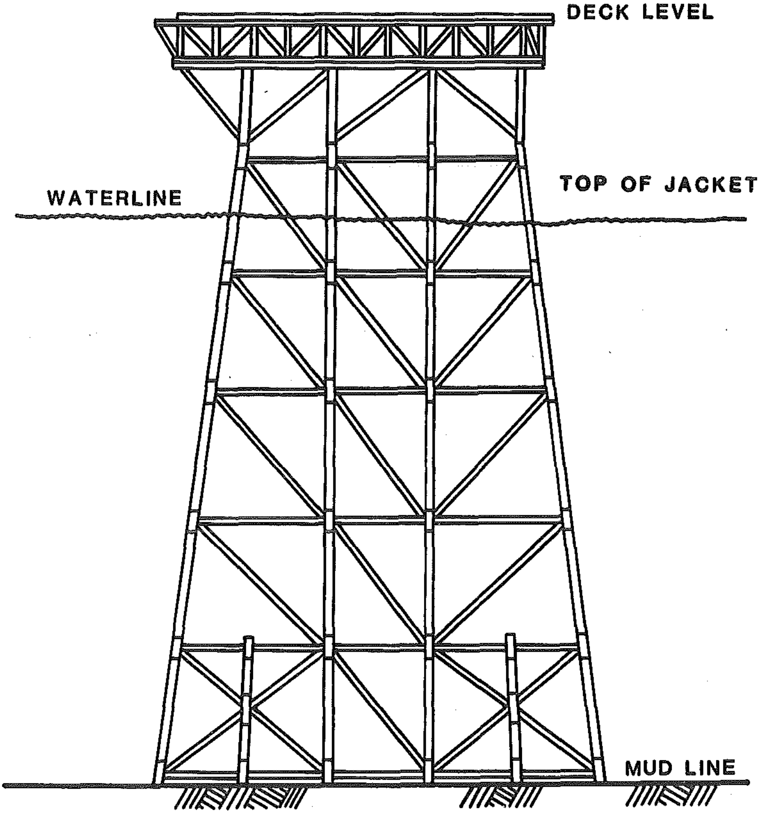

FIG. 1. Typical Jacket-Type Offshore Platform

this algorithm was approximately one-third the time required for the original analysis.

The members in jacket structures can be categorized on the basis of the change in the behavior of the remaining structure when a member fails. A quantitative classification system considering the change in the forces in the remaining members and the serviceability of the platform is presented in this paper. The original structure is assumed to be designed in the elastic range of the material. This assumption is consistent with current practice for the design of offshore platforms. Four member categories are proposed: non-redundant members; primary structural members I; primary structural members II; and redundant members. The significance of each category is discussed in this paper.

Load and Resistance Factor Design

All structures have an inherent risk of failure caused by uncertainty in the design process. This uncertainty arises because the load and the material properties are not known exactly. The objective of probabilistic design is to quantify the uncertainty so that risk can be evaluated.

Evaluating the uncertainty in the load and resistance variables, however, is an involved process. As a result, probabilistic design procedures have been cast into a load and resistance factor design format (LRFD). Such a design format accounts for the uncertainty with coefficients that modify the nominal load and resistance of the system.

The basic relationship of the LRFD format is presented by Galambos (1978) as:

$$\alpha R > \sum_{k=1}^{n} (\gamma S)_k \qquad (1)$$

The left side of Eq. 1 represents the resistance effects of the structural system. It contains the resistance factor, α, and the nominal resistance of the structure, R. The resistance factor decreases from unity as uncertainty in the calculated nominal resistance of the structure increases. The nominal resistance is calculated using interaction equations that are presented in design codes.

The right side of Eq. 1 represents the summation of all load effects that act on the structure. The term γ is the load factor associated with the load S. The total load the structure must withstand is the summation of all the individual loads that act on the system, e.g., live load, dead load, and wind loads. The load factor is used to modify the mean load effect and increases from unity as uncertainty in the mean load increases. A different load factor can be associated with each of the different load effects.

The basic form of the LRFD design format represented by Eq. 1 has been modified by Moses (1980) and has been recommended for use when designing fixed offshore oil production platforms. The modified form of Eq. 1 is:

$$\alpha_i \alpha_s R > \sum_{k=1}^{n} (\gamma_i \gamma_a S)_k \qquad (2)$$

In Eq. 2, the resistance factor is divided into two parts. The component resistance factor, α_i, is intended to account for uncertainty in the material properties and the strength of the fabricated components. The system consequence factor, α_s, is intended to reflect the importance of the component to the behavior of the entire structure, and any social and economic implications resulting from a failure of the structure. The load factor also has been divided into two parts. The load intensity factor, γ_i, is intended to cover variations in the load from the nominal expected value, and the load analysis factor, γ_a, is intended to cover those variations caused by theoretical assumptions and limitations of the analysis methods. The load and resistance factors in Eq. 1 have been separated into two parts in Eq. 2 to provide more flexibility in achieving uniform and consistent platform reliability.

Considerable work has been reported in the literature describing the character of the load effects, the component resistances, and the coefficients to modify these quantities. Among the authors are Anderson (1982), Bea (1980), Bjorhovde (1978), and Galambos (1978). The primary focus of the present paper is a method to rationally and consistently categorize the members of a fixed offshore platform so that appropriate system consequence factors can be selected.

Reanalysis Algorithm

When a member is removed from a structure, or when the stiffness of the structure changes because of material nonlinearity, the structural stiffness matrix, $\lfloor K \rfloor$, changes by an amount $\lfloor \Delta K \rfloor$. Under the influence of constant load, $\{F\}$, the original displacements, $\{X_0\}$, change by an amount $\{\Delta X\}$ when the stiffness matrix changes. This relationship is shown by:

$$\lfloor K - \Delta K \rfloor \{X_0 + \Delta X\} = \{F\} \quad (3)$$

Significant computational effort is required when using Eq. 3 to evaluate the effects of modifications to structures. Several different methods have been presented to reduce the computational effort required. These include modifying the inverse stiffness matrix (Kirsch 1972), initial strain concepts (Kavlie 1971), and reduced basis methods (Melosh 1968).

The reanalysis algorithm presented in this paper for member removal and for the nonlinear analysis after member removal is a modification of the initial strain concept of structural reanalysis. When using the initial strain concept, a modification to a structure is simulated by the application of additional load, $\{\Delta F\}$, to the original structure. The resulting displacements, $\{X\}$, are those that would be obtained if the modification had actually taken place. This relationship is shown by:

$$\lfloor K \rfloor \{X\} = \{F + \Delta F\} \quad (4)$$

The vector $\{\Delta F\}$ is selected such that Eq. 4 is true.

Modification for Member Removal

Structural modifications, in general, can involve any of the DOF in the structure. The modification for the removal of a single member, however, involves only the DOF that are associated with that member. Advantage can be taken of this fact when reanalyzing structures for the removal of members.

The strain energy stored in the original structure under the influence of the modified load $\{F + \Delta F\}$ is greater than the strain energy stored in the modified structure under the influence of the load $\{F\}$ by an amount U_j. The quantity U_j is the strain energy stored in member j, which is the member that is being removed from the structure. This relationship is:

$$0.5\{F + \Delta F\}^T\{X\} - U_j = 0.5\{F\}^T\{X\} \quad (5)$$

The first term on the left side of Eq. 5 is the strain energy in the original structure under the influence of the modified loads. The right side of Eq. 5 is the strain energy in the modified structure under the influence of the actual loads. From Eq. 5, it can be shown that the strain energy in the member being removed is:

$$U_j = 0.5\{\Delta F\}^T\{X\} \quad (6)$$

The strain energy in the same member can be computed using elemental displacements and forces as:

$$U_j = 0.5\{P_j\}^T\{x_j\} \quad (7)$$

$\{P_j\}$ are the elemental forces in member j and $\{x_j\}$ are the elemental displacements. Recalling that the elemental displacements can be computed from:

$$\{x_j\} = \lfloor B_j \rfloor^T \{X_j\} \quad (8)$$

where $\lfloor B_j \rfloor$ is the elemental transformation matrix. The vector $\{\Delta F\}$, then, can be found to be:

$$\{\Delta F\} = \lfloor B_j \rfloor^T \{P_j\} = \lfloor B_j \rfloor^T \lfloor k_j \rfloor \{x_j\} \quad (9)$$

where $\lfloor k_j \rfloor$ is the elemental stiffness matrix for element j. Eq. 9 was obtained by setting Eq. 6 equal to Eq. 7 and substituting Eq. 8. When Eq. 4 is solved for $\{X\}$ and substituted along with Eq. 8 into Eq. 9, $\{P_j\}$ is found to be:

$$\{P_j\} = \lfloor k_j \rfloor \lfloor B_j \rfloor \lfloor K \rfloor^{-1} \{F\} + \lfloor k_j \rfloor \lfloor B_j \rfloor \lfloor K \rfloor^{-1} \{\Delta F\} \quad (10)$$

The first term to the right of the equal sign in Eq. 10 is the force in member j, $\{P_{j0}\}$, in the original structure under the influence of the actual loads. If this substitution is made, Eq. 10 can be reduced to:

$$\{P_j\} = \{P_{j0}\} + \lfloor k_j \rfloor \lfloor B_j \rfloor \lfloor K \rfloor^{-1} \{\Delta F\} \quad (11)$$

After $\{P_j\}$ is computed using Eq. 11, $\{\Delta F\}$ can be computed using Eq. 9 and combined with the actual loads to determine the modified displacements. The inverse of the structural stiffness matrix in Eq. 11 does not have to be computed explicitly. Computations involving $\lfloor K \rfloor^{-1}$ can be performed implicitly using numeric procedures. A common method is Choleski decomposition.

Modification for Nonlinear Behavior

During the member categorization process, if the stress in any of the remaining members becomes inelastic, the nonlinear behavior of the structure must be considered. During the analysis for nonlinear behavior, more DOF need to be modified than for the removal of a single member, and the DOF to be modified are not known a priori. As such, the solution procedure needs to deal with the entire structure and cannot be expressed in terms of member forces and displacements as was done for the removal of a single member.

When Eqs. 3 and 4 are solved for the displacement vector $\{X\}$, and the resulting expressions are set equal to each other, the following expression can be obtained:

$$\{\Delta F\} = \lfloor dK \rfloor \{X_0\} + \lfloor \Delta K \rfloor \lfloor K \rfloor^{-1} \{\Delta F\} \quad (12)$$

Eq. 12 is not easily solveable for the modification load vector $\{\Delta F\}$. It can be solved, however, using the method of successive approximations. In Eq. 12, the quantity $\lfloor K \rfloor^{-1}\{\Delta F\}$ is equal to the modification displacement vector $\{\Delta X\}$. If this substitution is made into Eq. 12, the following expression is obtained:

$$\{\Delta F\} = \lfloor \Delta K \rfloor \{X_0 + \Delta X\} \quad (13)$$

The last estimate of $\{\Delta X\}$ can be used to compute a new value of $\{\Delta F\}$. This value of $\{\Delta F\}$ then can be used to compute a better estimate of $\{\Delta X\}$ which then can be be used to compute a still better estimate of $\{\Delta F\}$. This process is represented by:

$$\{\Delta F\}_i = \lfloor \Delta K \rfloor \{X_0 + \Delta X_{i-1}\} \quad i = 1, 2, 3, \ldots n \qquad (14)$$

where $$\{\Delta X_i\} = \lfloor K \rfloor^{-1} \{\Delta F_i\} \qquad (15)$$

The initial value of $\{\Delta X\}$ can be taken as being zero. The loop suggested by Eqs. 14 and 15 is repeated until the change between $\{\Delta X_{i-1}\}$ and $\{\Delta X_i\}$ is acceptably small.

Member Classification System

A quantitative member classification system is proposed to typify the consequences in a structural system caused by the failure of a single member within the system. Member classification is necessary to select the system consequence factors for design of the components. By classifying the components quantitatively, the same consequence factors can be assigned to all members that have a similar impact on the platform when they fail. The classification system proposed is intended for use with jacket-type offshore production platforms and utilizes changes in force and serviceability of the structure as the bases for classifying members.

Four member categories are proposed. These categories are:

1. Non-redundant member: the failure of this member necessitates a shutdown of the platform due to a loss of serviceability or a complete collapse of the system.
2. Primary structural member I: the failure of this member causes stress beyond the material elastic limit to be developed in some of the members in the platform, but the platform does not collapse.
3. Primary structural member II: the failure of this member causes a significant change in the behavior of the platform, but the level of stress in each of the remaining members in the platform remains in the elastic range of the material.
4. Redundant member: the failure of this member causes a negligible change in the behavior of the platform, and the level of stress in each of the remaining members in the platform remains in the elastic range of the material.

The consequences in a platform caused by the failure of a particular member can be different for each of the different load conditions. When a member can be placed into more than one failure consequence category, it is placed into the most severe category to which it can belong. Category 1, a non-redundant member, is the most severe category, while category 4, a redundant member, is the least severe. The quantitative significance of each category is discussed in the following sections.

Non-Redundant Member

The drilling/production platform collapses or the platform becomes unserviceable when a non-redundant member fails. For purposes of member categorization, collapse is considered to occur when an equilibrium configuration for the platform cannot be achieved or when the axial strain in a member exceeds twenty times the yield strain of the material. An equilibrium configuration cannot be achieved when a failure mechanism is formed. The system of equations implied by Eq. 11 has become singular, which implies that the structure has become unstable.

The serviceability of the platform must be considered when evaluating a failure of the platform. The usefulness of a structure is its ability to perform its intended function. The platform is not useful if all operations must cease; it has failed to satisfy its intended purpose. Although the failure due to a loss of serviceability is not as dramatic as the collapse of a platform, a loss of serviceability can have severe economic implications for the owner. Serviceability is not defined within the context of this paper because it will vary from one platform operator to the next and is also dependent upon the operations being performed on the platform. A potential measure of serviceability, though, would be the inclination of some reference plane within the structure, e.g., the inclination of the drilling deck.

Primary Structural Member

There are significant changes in the forces in the remaining members in a drilling/production platform when a primary structural member fails. The external loads that are applied to the platform are redistributed through the other members in the structure; the structure does not collapse. Also, the external loads are redistributed in such a manner that the platform does not become unserviceable.

The primary structural member category has been divided into two categories: primary structural member I and primary structural member II. The division between the two primary structural member categories is the transition from elastic to inelastic behavior of the material. When a primary structural member II fails, stresses in the other members in the platform change by at least 10% but remain in the elastic range of the material. When a primary structural member I fails, the level of stress in

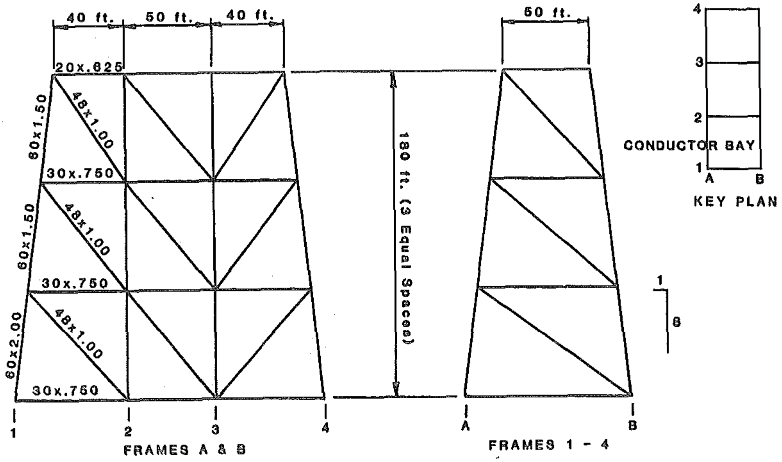

FIG. 2. Diagonally Braced Platform Example

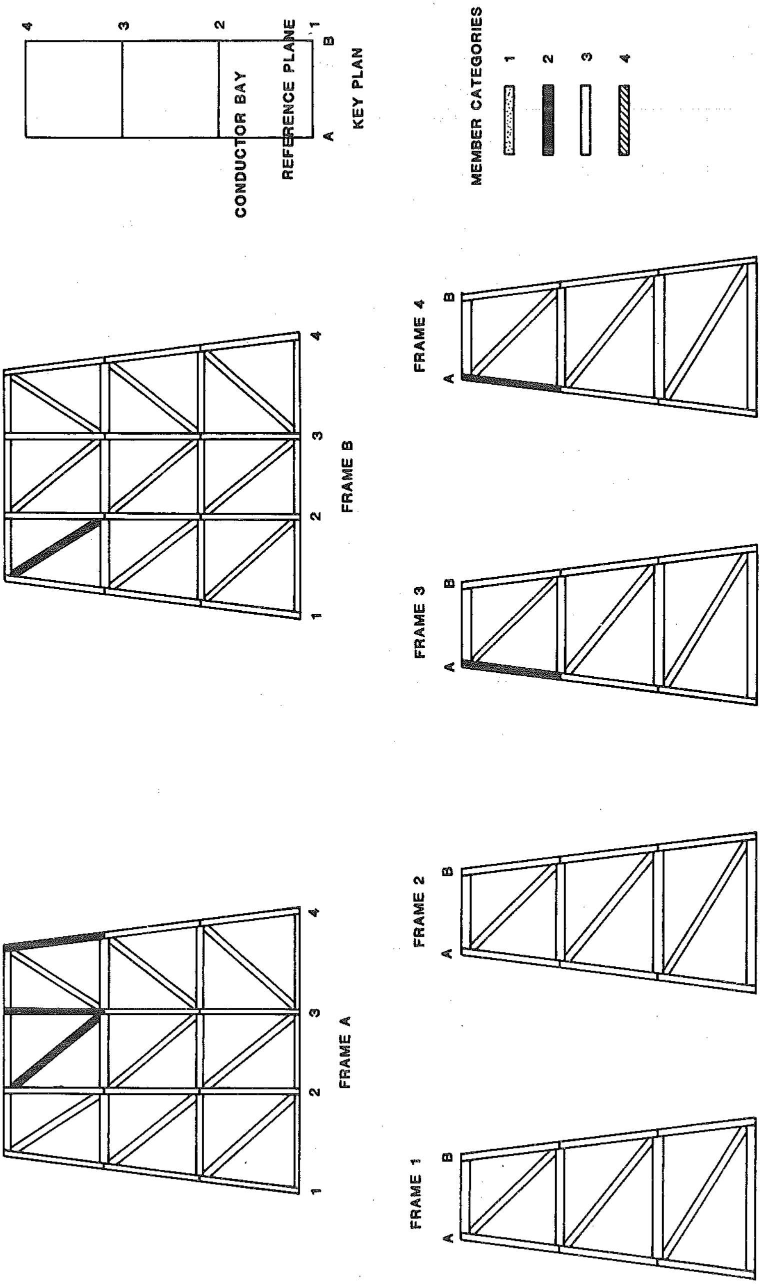

FIG. 3. Classification of Members in a Platform Subjected to a Southwest Wave

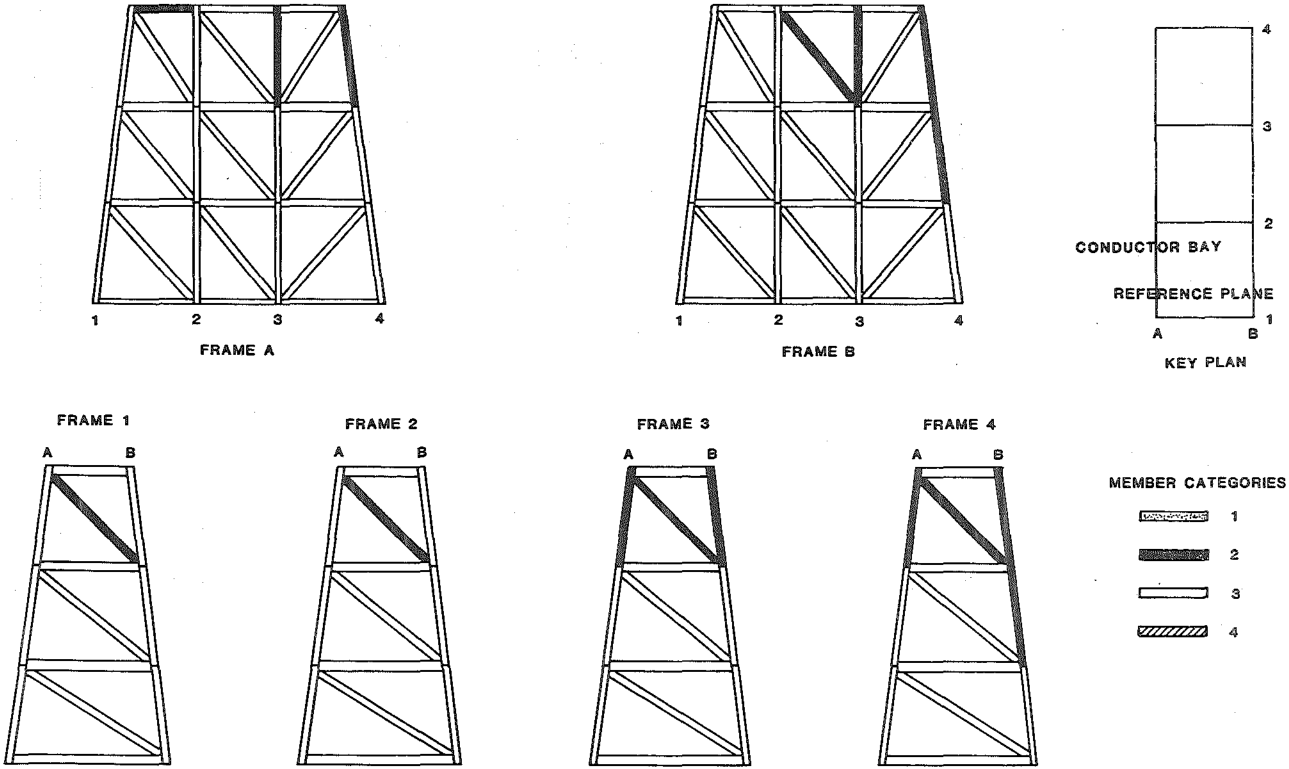

FIG. 4. Classification of Members in a Platform Subjected to a Southeast Wave

some of the other members in the platform exceeds the yield stress of the material.

To separate the two categories of primary structural members, first yield was used to indicate the transition from elastic to inelastic behavior of a member. Before first yield, the member behaves in an elastic manner. After first yield, the member behaves in a perfectly plastic manner. The equations in the American Institute of Steel Construction (AISC) steel manual (AISC 1980) with the safety factors removed were used to indicate first yield [Nelson 1983(b)]. Kallaby (1975) indicated first yield in a similar manner.

Redundant Member

There are negligible changes in the forces in the other members of the platform structure when a redundant member fails. Also, when a redundant member fails, the level of stress in other members continues to be in the elastic range of the material and the remaining platform is serviceable.

For the classification system presented in this paper, a change in force in the remaining members of the platform of less than 10% was considered negligible. Such a change implies a change in the stresses of less than 10%. Jacket-type offshore platforms are constructed of large diameter tubular sections. These sections can be treated as annular rings, for practical purposes, when computing the cross-sectional characteristics of the member and the stresses within the member. When treating the tube as an annular ring, all of the cross-sectional characteristics become a linear function of the wall thickness of the pipe. The American Petroleum Institute permits wall thickness to vary by 10%; therefore, the stress in the member can vary by 10%. Variation in the wall thickness of a member produces uncertainty that is accounted for by the component resistance factor. As such, a force change of less than 10% was considered negligible for the purpose of determining the system consequence factor.

Application of Member Classification System

The application of the member classification system presented in this paper can be demonstrated by considering the diagonally braced platform structure shown in Fig. 2. For simplicity, the loads acting on the platform have been idealized. A vertical force of 1,500 kips directed downward was applied to the top of each leg which represents an average load of 600 psf on each deck of the two-level deck structure. The effects of wind, wave, and current were simulated by applying a horizontal force of 1,000 kips at the top of each leg. The horizontal load was applied from the southeast in one load condition and from the southwest in the second load condition.

The results of member classification for each load case are presented in Figs. 3 and 4. All of the members in the platform are not classified the same in each of the loading conditions. Consider, for example, the top horizontal member in frame *A*. In one load case the member is classified as category 3, which is a primary structural member II. In the second load case the member is classified as category 2, which is a primary structural member I. The final classification of this member would be category 2 because this category is the most severe of all the possible categories into which the member can be placed. Presented in Fig. 5 is the final classification of the

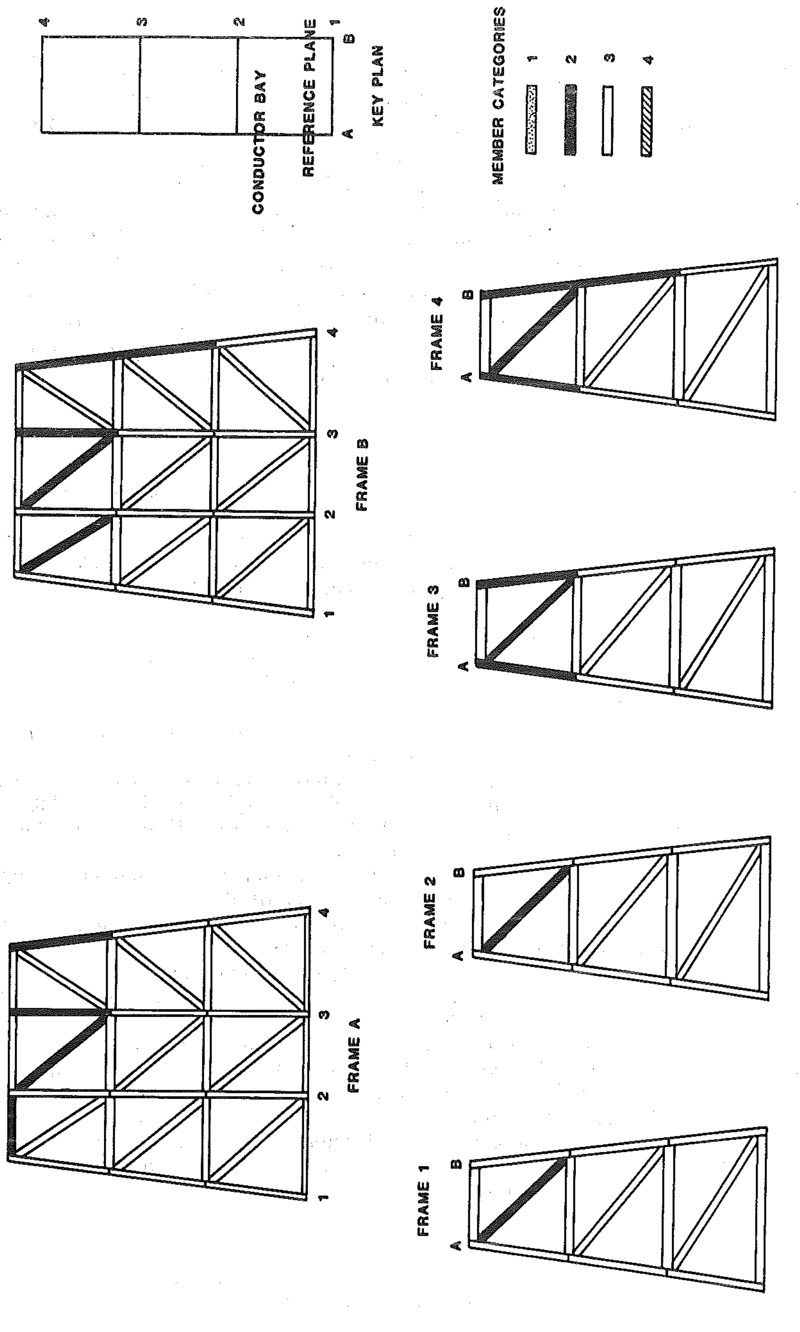

FIG. 5. Final Classification of Members in a Platform

members in the structure. This is the classification of the members that would be used for design.

Other platform configurations and different loads acting on the platform would be evaluated in the same manner. The results obtained when evaluating other platforms and loads would be different, but the results would be interpreted in the same manner as the results presented in this example. This procedure provides a consistent and quantitative basis for categorizing the members in jacket-type platform structures.

The component classification procedure discussed in this paper has a secondary advantage during platform design. Components that have a negligible influence on the strength of the platform become evident. These are the category 4 members. A change in design or a change in platform geometry could reduce the number of category 4 members, thereby obtaining greater economy. Likewise, the number of category 1 members could be reduced which would result in increased platform safety.

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Appendix II. Notation

The following symbols are used in this paper:

$\lfloor B_j \rfloor$ = transformation matrix for member j;
$\lfloor K \rfloor$ = structural stiffness matrix;

$[\Delta K]$ = modification to structural stiffness matrix;
$[k_j]$ = elemental stiffness matrix for member j;
$\{F\}$ = load vector;
$\{\Delta F\}$ = modification to load vector;
$\{P_j\}$ = force vector for member j;
$\{X\}$ = displacement vector;
$\{\Delta X\}$ = change in displacement vector;
$\{x_j\}$ = elemental displacement vector for member j;
U_j = strain energy in member removed;
α = resistance factor;
α_i = component resistance factor;
α_s = system consequence factor;
γ = load factor;
γ_a = load analysis factor; and
γ_i = load intensity factor.