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no. 6

Potential Failure of Surface Ship and Submarine Drydock Blocking Systems Due to Seismic Loadings and Recommended Design Improvements

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U.S. naval shipyards are located in regions where significant earthquakes occur. This paper describes a nonlinear material model for drydock block caps. It is determined that submarine drydock blocking systems would fail at accelerations which are significantly lower than the Navy's 0.2 *g* survival requirement. Natural rubber caps and dynamic isolators are analyzed to determine their potential for increasing system survivability. When incorporated in blocking systems, significant increases in survivability occur; however, eleven submarine systems studied still fail well below the required level. A three-degree-of-freedom submarine drydock blocking system computer-aided design package is developed. The computer program is verified by a case study of the USS *Leahy* (CG-16) earthquake sliding failure. System survivability using site-specific earthquakes with differing frequency spectrums is studied. Two adequate design solutions are found. The low-stiffness solution uses dynamic isolators and rubber caps, and the high-stiffness solution uses wale shores and rubber caps.

CURRENTLY submarines are routinely drydocked in graving docks at three locations on the West Coast and five locations on the East Coast of the United States. They also can be docked in graving docks and shiplift systems at many additional locations on both coasts if required. When a submarine is in one of these docks it is susceptible to any ground motion that may occur. Figure 1 [1][5] illustrates the locations where submarines can be placed in graving docks. This figure also indicates where earthquakes have historically occurred.

The locations of the West Coast shipyards coincide with the areas of highest earthquake risk. Even on the East Coast, earthquakes of significant magnitude have been known to occur where submarines now are drydocked. On the East Coast, Portsmouth Naval Shipyard and Charleston Naval Shipyard are located in the highest-risk zones.

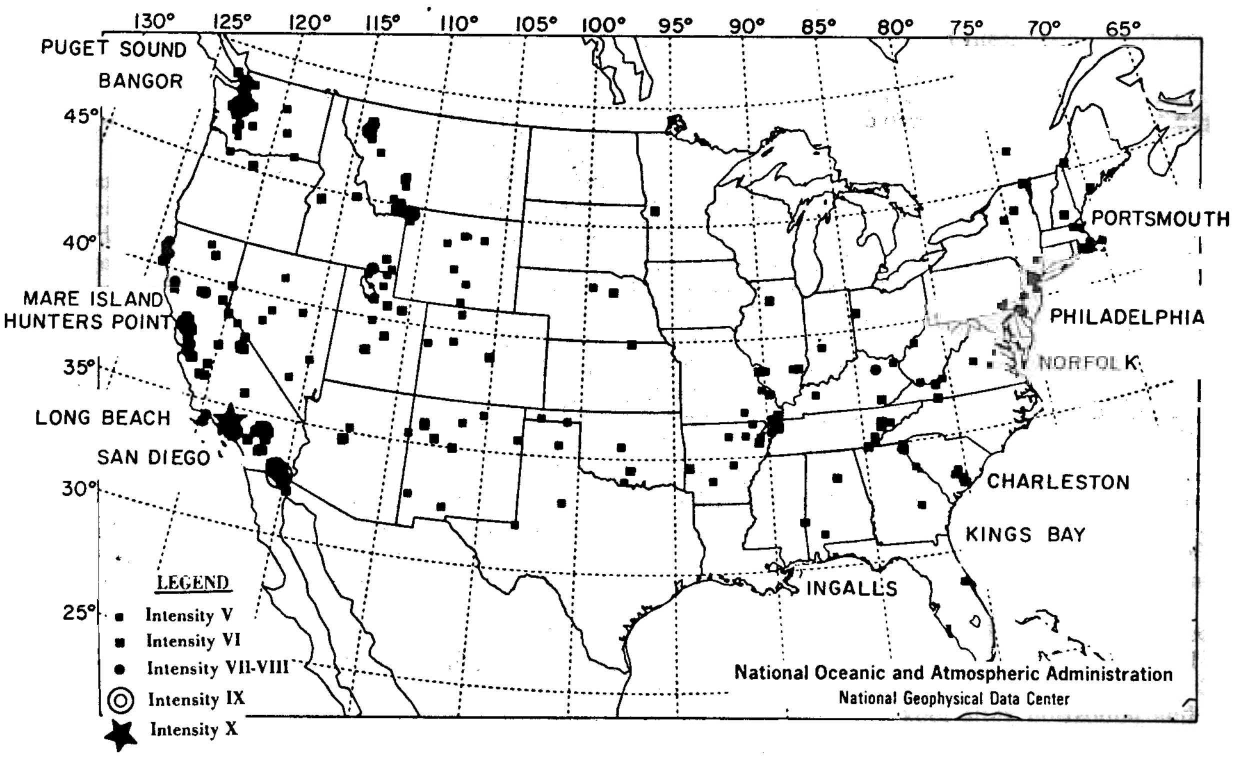

Fig. 1 Earthquake history of the United States through 1980 and shipyard locations

is located primarily on landfill, which is known to be tremendously susceptible to earthquake damage.

On October 1, 1987 a magnitude-5.9 earthquake hit Whittier, California, which is approximately 20 miles northeast of Long Beach. Long Beach Naval Shipyard had accelerographs located in graving dry docks 1 and 2. These devices all produced acceleration time histories for this earthquake. Significant motion was felt in the shipyard. The cruiser USS *Leahy*, which was in dry dock No. 3, experienced side block shifting during the earthquake.

Earthquakes can occur virtually anywhere in the United States where submarines can be drydocked. They can produce tremendous forces and ground displacements which seriously threaten the safety of drydocked submarines. Earthquakes usually occur without any warning. They reach maximum strength within seconds. Presently there is no reliable means of predicting the occurrence of earthquakes. Therefore, if submarines are to continue to be drydocked in earthquake high-risk areas the drydock blocking systems must be designed to resist expected earthquake excitation.

Submarine drydock blocking system analysis history

The major objective in the design of the docking block arrangements for Navy ships is to provide blocking systems which are adequate to support the ship's weight and to survive earthquake motions up to an intensity which will destroy the dock itself. Presently, these design methods involve approximating the seismic response by using a specified horizontal acceleration, the magnitude of the peak acceleration being 0.2 *g*. The potential for overturning, sliding, or crushing of the blocking system is then assessed on an "equivalent static" basis with a horizontal force applied at the ship's center of gravity.

A more rigorous examination of the seismic response of submarines was undertaken by Viscomi (1981) [3], using a dynamic equation of motion. This analysis involved determining peak ground accelerations which would cause the submarine to lift off one set of side blocks for a variety of blocking arrangements. The submarine was considered to be a rigid body with a single (rotational) degree of freedom. The docking blocks were thus necessarily assumed to be stable and to respond elastically to load.

Using the quasi-static method it was found that present drydock blocking systems could survive an earthquake of the magnitude of the 1940 El Centro earthquake (0.45 *g* peak acceleration). However, studies conducted at M.I.T. under the direction of D. G. Karr, analyzing the problem using one-degree-of-freedom [4], two-degrees-of-freedom [5], and three-degrees-of-freedom [6] models, indicated that failure would occur at substantially lower earthquake magnitudes.

This significant discrepancy warranted further examination and verification. The results from a one, two, and three-degrees-of-freedom reanalysis by Karr [7] indicated that eleven submarine systems could withstand only approximately 13 to 25 percent of the El Centro earthquake ground motion amplitudes. A two- or three-degrees-of-freedom method is required to determine the exact blocking system failure modes. The four modes of failure of the blocking system addressed were:

- crushing of the keel and bilge blocks,
- sliding of the block interfaces,
- overturning of the blocks, and
- lifting off of the ship from port or starboard side blocks or keel blocks.

Development of the three-degrees-of-freedom earthquake-resistant drydock blocking design package

Three-degrees-of-freedom computer program background

The computer program used to analyze the submarine drydock blocking systems in this paper was developed by Hepburn and Luchs and is based on the program developed by Sigman [6]. Many significant modifications are made to Sigman's program and several support programs are written to improve the usefulness of this program as a design tool. These modifications include the addition of the subroutines, "BILINALL" and "RUBBER" to incorporate nonlinear stiffnesses of blocking materials. The nonlinear (bilinear) material models developed are described later. Other significant modifications made include the addition of horizontal and vertical acceleration inputs, force and displacement outputs, and changes to the equations of motion to include more complex geometry. The geometry changes took into account the effects of side block height, cap angle, and the inclusion of wale shores. In addition, the side block wedge effect on the sliding failure mode is included in the program.

The main program, "3DOFRUB," inputs submarine drydock blocking system parameters and then calculates the system's modal masses, stiffnesses, damping coefficients, and natural frequencies. The horizontal acceleration time history (and vertical if applicable) are input using the "ACCLINPT" subroutine. The main loop of the program solves the equations of motion using the fourth-order Runge-Kutta numerical method. The blocking material stiffnesses are recalculated each time step using the appropriate subroutines. Each time step, keel and side block forces are calculated, and the system is tested for failure.

The program begins by using 100 percent of the input acceleration time history. It carries out repeated loops through the whole history, each time decreasing the input acceleration. This continues until the system survives a complete loop through the time history. Force and displacement data files as chosen by the user are created by the subroutine "RESPALL" for use in plotting system response.

Development of miscellaneous support programs

Several support programs are developed to produce acceleration time history data files usable by 3DOFRUB. The first program, "V2READ$," creates acceleration data files from standard format magnetic media data files. The second program, "ACCELMOD," modifies an acceleration data file in single-column format by adding a new data point found by linear interpolation between each original data point. This is necessary in some cases to improve the accuracy of the numerical computational scheme.

The third computer program, "DATINNEW," reads acceleration data from ASCII data files and modifies it in several ways. The program adds character string labels (name of the earthquake, acceleration component name, and acceleration time step) to the output data file. DATINNEW allows the user to produce an output data file of any length up to the maximum number of entries in the input data file. The program also allows the user to multiply each data point by a desired constant to produce earthquake time histories of varying magnitudes. Another program, "MAKERUB," is developed to create submarine and blocking system data input files for 3DOFRUB. This computer program allows the user to prepare new data files or modify existing data files.

Geometrical improvements to the three-degrees-of-freedom model and computer program

Geometrical improvements to the three-degrees-of-freedom equations of motion

The three-degrees-of-freedom model of the submarine drydock blocking system at rest as developed by Sigman [6] is used as a baseline for this paper. Figure 2 is a two-dimensional representation of the submarine and dry dock with the keel and side block piers modeled as horizontal and vertical springs and dashpots.

This figure differs from Sigman's model in several respects. First, wale shores, modeled as horizontal springs and dashpots, at a distance *AAA* from the keel are added. Second, the height of the side blocks above the keel baseline and the resulting angle, alpha, between the baseline and a line through the keel and side block point of contact are shown and taken into account in the equations of motion.

The point CG1 is the initial location of the center of gravity of the submarine. The point *K* is the initial location of the keel of the submarine. The point *K'* (Fig. 3 insert) is the location of the keel after horizontal and vertical translation has occurred. Rotation occurs about this point. *KG* is the distance from the keel to the center of gravity. The distance *br* is the transverse distance between the center of the caps of the port and starboard side blocks. The horizontal, vertical, and wale shore spring constants are as designated in the figure.

The system is excited by horizontal and vertical dry dock accelerations $\ddot{x}_g$ and $\ddot{y}_g$, respectively. The entire dry dock and submarine system moves relative to a fixed reference frame. The excited system is shown in Fig. 3. The system of equations is expressed in terms of motion of the submarine relative to the dry dock. The point CG2 in the figure is the location of the center of gravity of the submarine relative to the fixed reference frame after horizontal displacement u and vertical displacement v. The point CG3 is the location of the submarine's center of

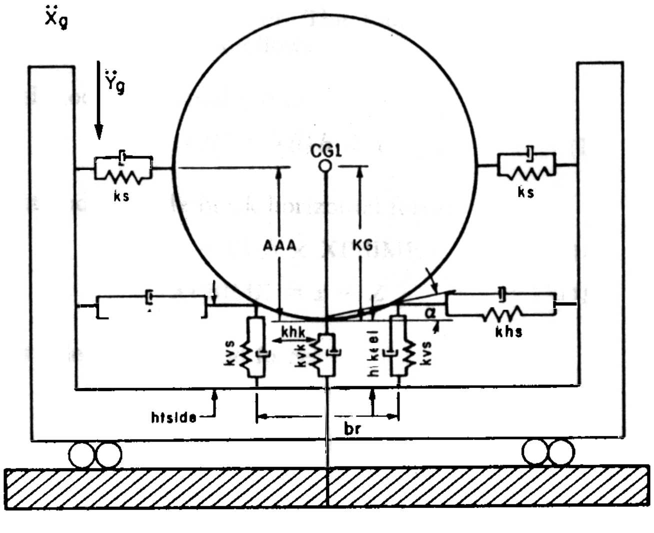

Fig. 2 Three-degrees-of-freedom submarine drydock blocking system model at rest

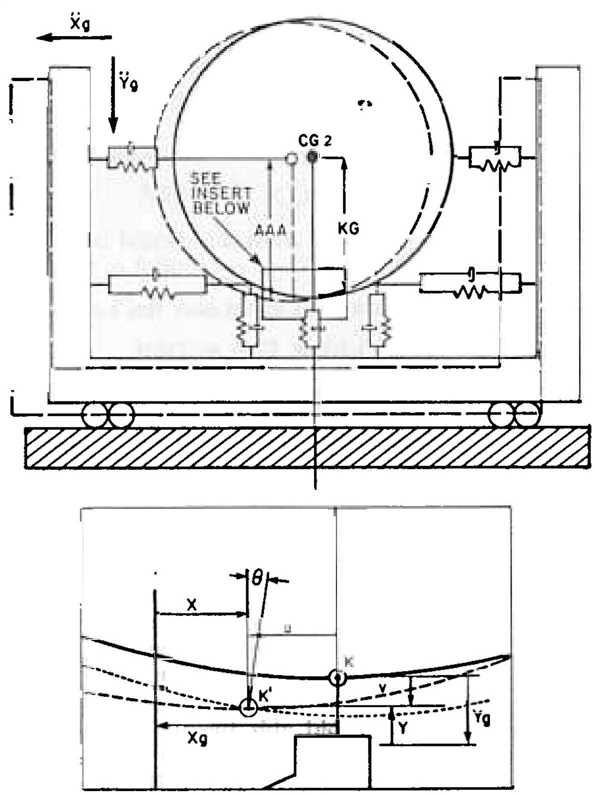

Fig. 3 Three-degrees-of-freedom submarine drydock blocking system model excited

gravity after the additional absolute rotation, theta. The displacements illustrated are described as follows:

The relative horizontal displacement coordinate x is the displacement of the submarine keel with respect to the dry dock. The displacement u is the position of the keel relative to the fixed reference frame. With ground motion x_g the following equations hold:

$$x = u - x_g$$
$$u = x + x_g$$
$$\ddot{u} = \ddot{x} + \ddot{x}_g \quad (1)$$

Similarly for vertical translation the following equations hold:

$$y = v - y_g$$
$$v = y + y_g$$
$$\ddot{v} = \ddot{y} + \ddot{y}_g \quad (2)$$

The coupled nonlinear three-degrees-of-freedom equations describing the system motion as developed by Sigman are as follows:

$$M\ddot{x} + M\overline{KG}\,\ddot{\theta} + C_x\dot{x} + C_{x\theta}\dot{\theta} + (2khs + khk)x = -M\ddot{x}_g \quad (3)$$

$$M\ddot{y} + C_v\dot{y} + (2kvs + kvk)y = -M\ddot{y}_g \quad (4)$$

$$I_k\ddot{\theta} + M\overline{KG}\,\ddot{x} - M\overline{KG}\,\ddot{y}\,\theta + C_\theta\dot{\theta} + C_{\theta x}\dot{x} + [(br^2/2)kvs - W\overline{KG}]\theta = -M\overline{KG}\,\ddot{x}_g \quad (5)$$

In equations (3) through (5), M is the mass of the submarine, I_k is the rotational moment of the submarine about the keel, and W is the weight of the submarine.

Sigman's analysis assumed that the height of the keelblocks was the same as the height of the side blocks. Taking the actual height of the side block into account gives the following expression for this lever arm:

$$LLL = [(\text{htside} - \text{htkeel})^2 + (br/2)^2]^{1/2} \quad (6)$$

The angle alpha is then

$$\alpha = \text{Sin}^{-1}\,[(\text{htside} - \text{htkeel})/LLL] \quad (7)$$

There are additional vertical and horizontal displacements of the side block cap due to rotation (θ) of the submarine about the keel. Assuming small rotation angles, the displacement of the cap due to rotation is $L\theta$. The vertical component of $L\theta$ is R, and the horizontal component is Z. From side block geometry the following expression for R is found:

$$R = L\theta \times \cos(\alpha) \quad (8)$$

In the case where $BU = 0$ (side block height = keelblock height), as was the case in Sigman's analysis, equation (8) reduces to

$$R = L\theta \quad (9)$$

In this case $L = br/2$ and therefore

$$R = (br/2) \times \theta \quad (10)$$

Similarly

$$Z = L\theta \times \sin(\alpha) \quad (11)$$

In the case where $BU = 0$ and $L = br/2$:

$$Z = L\theta \times \sin(0) = 0 \quad (12)$$

R and Z are used in calculating the horizontal and vertical forces on the side blocks. Without these geometric relationships, the horizontal force exerted on the side blocks of submarines due to rotation is not taken into account. Not including this force is a significant underestimate of the true horizontal forces seen by the side blocks. Including this effect represents an important improvement to Sigman's model.

With these equations incorporated into the 3DOFRUB computer program, the model is now general enough to take into account the high buildups of surface ships. Even though for submarines, including the geometric side block effects changes the survivability of the systems by approximately only 1 percent, for ships with higher buildups these effects will be larger. The total blocking system forces are calculated as follows:

Keel block horizontal force:

$$RR1 = khkb \times x \quad (13)$$

Right and left side block horizontal force:

$$RR2 = khsb \times \text{XPRIME} \quad (14)$$

$$\text{XPRIME} = x + Z \quad (15)$$

Left side block vertical force:

$$RR3 = kvsb1 \times \text{YPRIME1} \quad (16)$$

$$\text{YPRIME1} = -y - R + \text{DELTA} \quad (17)$$

Right side block vertical force:

$$RR4 = kvsb2 \times \text{YPRIME2} \quad (18)$$

$$\text{YPRIME2} = -y + R + \text{DELTA} \quad (19)$$

Keelblock vertical force:

$$RR5 = kvkb \times \text{YPRIME3} \tag{20}$$

$$\text{YPRIME3} = -y + \text{DELTA} \tag{21}$$

Right and left wale shore horizontal force:

$$RR6 = ks \times (x + AAA \times \theta) \tag{22}$$

The total blocking system moments about the keel are calculated as follows:

Right and left side block horizontal moment:

$$MM1 = RR2 \times LLL \times \sin(\alpha) \tag{23}$$

Left side block vertical moment:

$$MM2 = RR3 \times LLL \times \cos(\alpha) \tag{24}$$

Right side block vertical moment:

$$MM3 = RR4 \times LLL \times \cos(\alpha) \tag{25}$$

Right and left wale shore horizontal moment:

$$MM4 = RR6 \times AAA \tag{26}$$

DELTA is the static deflection of the side and keelblocks due to the submarine's weight. The value of DELTA is calculated in each loop of 3DOFRUB and depends on the values of the current side block and keelblock vertical stiffnesses. All blocking stiffnesses are those found from appropriate BILINALL or RUBBER subroutines. If a linear material analysis is selected by the program user, linear material stiffness values are used.

To derive the modified submarine drydock blocking system equations of motion, the following procedure is used. First the forces in horizontal direction are summed and equated with the masses times acceleration in that direction. Next, the forces in the vertical direction are summed and equated with the masses times acceleration in that direction. Finally, the moments are summed about the keel and equated with the rotational inertia times rotational acceleration. After combining terms and simplifying, the modified equations of motion which include wale shore and side block geometric effects are as follows:

$$M\ddot{x} + M\overline{KG}\,\ddot{\theta} + C_x\dot{x} + C_{x\theta}\dot{\theta} + (2ks + 2khs + khk)x + [2ks \times AAA + 2khs \times LLL \times \sin(\alpha)]\,\theta = -M\ddot{x}_g \tag{27}$$

$$M\ddot{y} + C_y\dot{y} + (2kvs + kvk)\,y = -M\ddot{y}_g \tag{28}$$

$$I_k\ddot{\theta} + M\overline{KG}\,\ddot{x} - M\overline{KG}\,\ddot{y}\,\theta + C_\theta\dot{\theta} + C_{\theta x}\dot{x} + [2ks \times AAA + 2khs \times LLL \times \sin(\alpha)]\,x + \{2ks \times AAA^2 + 2khs \times [LLL \times \sin(\alpha)]^2 + (2 \times kvs) \times [LLL \times \cos(\alpha)]^2 - W\overline{KG}\}\,\theta = -M\overline{KG}\,\ddot{x}_g \tag{29}$$

The three-degrees-of-freedom equations (27) through (29) are now stiffness as well as inertially coupled. In matrix form, there are now two new elements in the stiffness matrix ($K_{13} = K_{31}$), where $K_{13} = [2ks \times AAA + 2khs \times LLL \times \sin(\alpha)]$. The first term, $2ks \times AAA$, is due to wale shores and the second term, $2khs \times LLL \times \sin(\alpha)$, is due to the effect of system rotation on the side blocks. The stiffness matrix elements K_{11} and K_{33} are also modified to include these effects.

Effect of side block cap angle on system sliding failure mode

All failure modes incorporated in the 3DOFRUB computer program are the same as those used by Sigman [6] except for the side block sliding failure mode. A more general approach is used to model the side block sliding forces. This allows this program to be used for surface ship block geometries as well as submarines. One additional data input required by the program is the side block cap angle. An average value of side block cap angles, obtained from the submarine docking drawings, is used in this paper. It is possible to model the failure of the different side blocks along the length of the submarine or ship by running the program separately for each side block right and left set.

Figure 4 shows the geometry used in the modeling of the side block cap. The side block cap is modeled as a wedge. The outward force, $hf2$, is caused by the relative rigidity of the ship compared with the side blocks. When a vertical force occurs, it tends to push the block outboard rather than move the ship inboard. The equations describing the forces associated with the side blocks due to this wedge effect and other frictional forces are as follows:

Outboard horizontal forces:

$$hf1 = RR2 \tag{30}$$

$$hf2 = RR3 \times \cos(\beta) \times \sin(\beta) \tag{31}$$

Resisting horizontal forces:

$$hf3 = u2 \times RR3 \times \cos(\beta) \times \sin(\beta) \tag{32}$$

$$hf4 = u1 \times RR3 \tag{33}$$

where

β = side block cap angle
$u1$ = block on block friction coefficient
$u2$ = hull on block friction coefficient

In the figure, $rf1 = RR3$. $RR2$ and $RR3$ are defined in equations (14) and (16), respectively. If $rf1$ and $hf1$ are acting in the direction shown in Fig. 4, 3DOFRUB flags side block sliding failure if $hf1 + hf2$ is greater than $hf3 + hf4$.

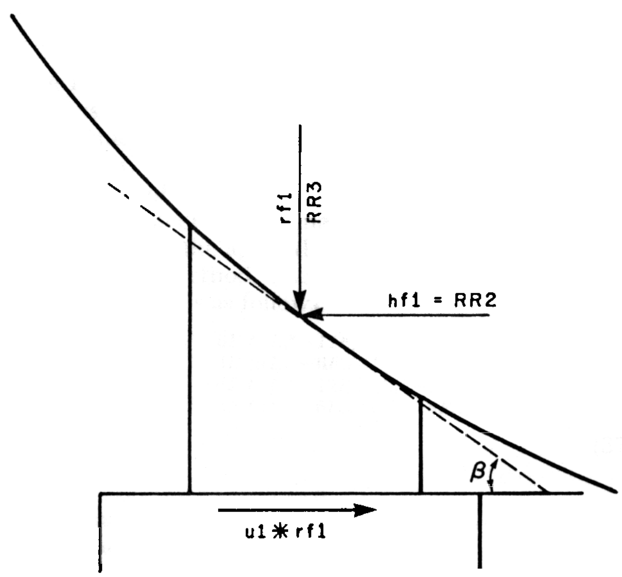

Fig. 4 Side block sliding forces

Existing and potential blocking material characteristics and properties

Existing blocking materials

Virtually all U.S. naval shipyards and private yards which dock U.S. Navy ships use softwoods and hardwoods as drydock blocking materials. Concrete is used in the base of most of the blocking piers; however, the wood products comprise the upper portion of the blocking system, which is in contact with the ship. The softwood is used in a "soft cap" (2 to 6 in.) on top of the hardwood to protect the hull from stress concentrations.

Previous analyses assumed that all the blocking materials were linear, elastic, and isotropic. While these are reasonable assumptions for concrete, that is not the case for wood. Typically the softwood used in drydock blocking systems is Douglas fir. The hardwood used is usually white oak. The capping and hardwood materials that shipyards receive from their suppliers have highly variable properties. Figure 5, a photograph of the keelblocking system of the USS *Leahy*, shows a typical blocking arrangement.

General wood properties

When a drydock blocking system is constructed by a shipyard, either new wood just obtained or old wood on hand is used. This applies to the soft cap and hardwood portions of the system. Sometimes new wood is combined with old wood in random ways in the same blocking pier. Because the wood used comes from various parts of the country, the moisture contents and ring sizes and thus strength properties of the wood vary dramatically. Therefore, blocking piers in use today contain materials which have uncertain characteristics.

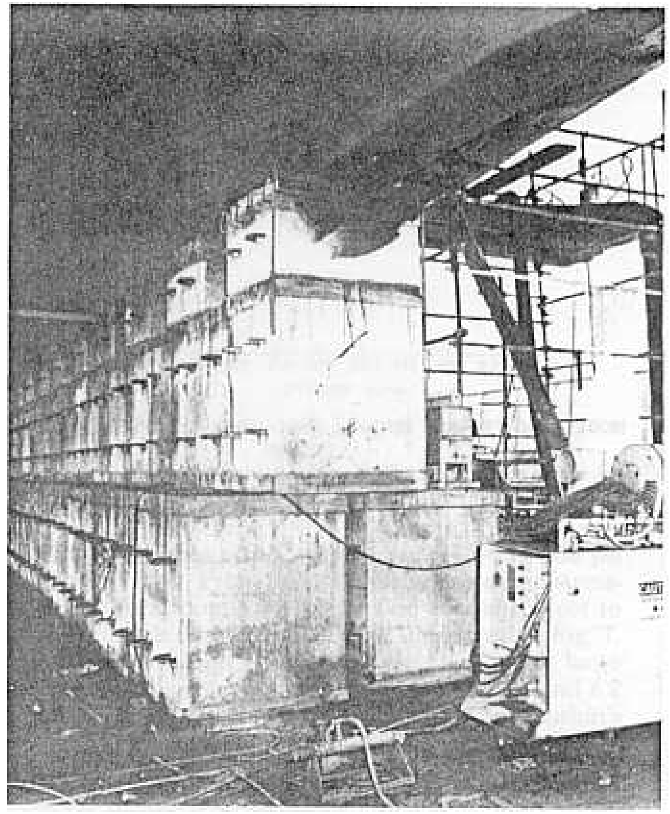

Fig. 5 USS *Leahy* keelblocking system (official U.S. Navy photograph, Long Beach Naval Shipyard)

Determination of drydock blocking pier stiffnesses

With the inclusion of many different types of materials in one side block or keelblock pier, a method was needed to determine the horizontal and vertical pier spring constants. In this paper, the piers are modeled in the horizontal direction as cantilever beams and shear elements. In the vertical direction they are modeled as axially loaded columns. In both directions they are considered to be composite elements with different properties along the length. The procedure used to calculate keel vertical stiffness was a standard addition of element stiffnesses in series as follows:

$$kvk' = 1/[(1/k_{\text{rubber}}) + (1/k_{\text{fir}}) + (1/k_{\text{oak}}) + (1/k_{\text{concrete}})] \quad (34)$$

where kvk' is the stiffness of one keel pier. This required knowing each layer's dimensions and modulus of elasticity. This information was obtained from the appropriate submarine docking drawing. The stiffness of an individual layer is given by

$$k = EA/L \quad (35)$$

where

E = modulus of elasticity of layer
L = height of layer
A = area over which vertical force is applied

For some layers the cross sections varied over the layer or there were abrupt transitions from one layer to the next. In these cases an effective area was used based on the standard 1 to 3 load distribution slope employed by the Naval Sea Systems Command. This procedure was used to calculate the stiffness of one individual keel pier. To determine the stiffness of the entire keel system the individual keel pier stiffness was multiplied by the number of keelblocks. Side pier vertical stiffnesses were determined in a similar manner.

For the computation of horizontal stiffness, two types of horizontal deformation must be considered: the horizontal cap displacement due to bending and the horizontal cap displacement due to shear. The total keel pier stiffness coefficient for one keel pier (khk') is then given by

$$khk' = P/(d_b + d_s) \quad (36)$$

where P is the horizontal force applied to surface of the cap; d_b is the displacement of the cap's surface due to bending and d_s is the displacement of the cap's surface due to shear.

In the case of bending, the block is modeled as a four-element cantilever beam. The displacement of the top of this beam due to the applied force P is determined by the stiffness matrix method. The stiffness matrix equation for the first element is as follows:

$$\begin{bmatrix} Q_1 \\ M_1 \\ Q_2 \\ M_2 \end{bmatrix} = \begin{bmatrix} 12E_1I_1/L_1^3 & 6E_1I_1/L_1^2 & -12E_1I_1/L_1^3 & 6E_1I_1/L_1^2 \\ 6E_1I_1/L_1^2 & 4E_1I_1/L_1 & -6E_1I_1/L_1^2 & 2E_1I_1/L_1 \\ -12E_1I_1/L_1^3 & -6E_1I_1/L_1^2 & 12E_1I_1/L_1^3 & -6E_1I_1/L_1^2 \\ 6E_1I_1/L_1^2 & 2E_1I_1/L_1 & -6E_1I_1/L_1^2 & 4E_1I_1/L_1 \end{bmatrix} \begin{bmatrix} q_1 \\ \theta_1 \\ q_2 \\ \theta_2 \end{bmatrix} \quad (37)$$

where

E_1 = modulus of elasticity of element number 1
I_1 = moment of inertial of element 1's cross section
L_1 = length of element 1
Q's = nodal forces

M's = nodal moments
q's = nodal displacements
θ's = nodal rotations (radians)

The elemental stiffness matrix equations are determined in a similar fashion for elements 2, 3, and 4. They are then combined to form a ten-by-ten stiffness matrix. The combined stiffness matrix equation is then solved to determine the displacement (d_h) at the top of the beam due to force P. In shear the block is modeled as a composite element subject to shear stress at the top of each layer. For element 1 the following equation holds:

$$\gamma_1 = (P/A_1)/G_1 \tag{38}$$

γ_1 = shear strain in element 1
P = horizontal force acting on surface of element 1
G_1 = modulus of rigidity of element 1
A_1 = top contact area

The following formulas were used in this paper to determine the moduli of rigidity for the layer materials:

Element 1 (concrete): $G = 0.6E$ [8] (39)
Elements 2 and 3 (Douglas fir and oak):
$G_{LR} = (1/14)E_L$ [8] (40)
Element 4 (rubber): $G = 0.339E$ [9] (41)

The shear displacement was determined using

$$d_s = \gamma_1 L_1 + \gamma_2 L_2 + \gamma_3 L_3 + \gamma_4 L_4 \tag{42}$$

The total horizontal stiffness for a row of blocks is the value of khk' times the number of keelblocks. Similar procedures are used employing four layers to determine the side block pier horizontal stiffnesses.

Determination of blocking wood properties

Douglas fir and oak used in U.S. Navy drydock blocking systems are nonlinear anisotropic materials. Their properties are functions of many different variables. For this paper, the Douglas fir caps are modeled as bilinear materials. This means that up to the fiber stress proportional limit (FSPL) the Douglas fir has an initial constant modulus of elasticity. When subject to additional stress, the wood undergoes plastic deformation and the modulus of elasticity changes to a lesser value. This modulus is in effect until ultimate stress (about 700 psi) is reached. This model for Douglas fir is based on the compressive stress-strain curve illustrated in Fig. 6 [12]. The two moduli obtained from

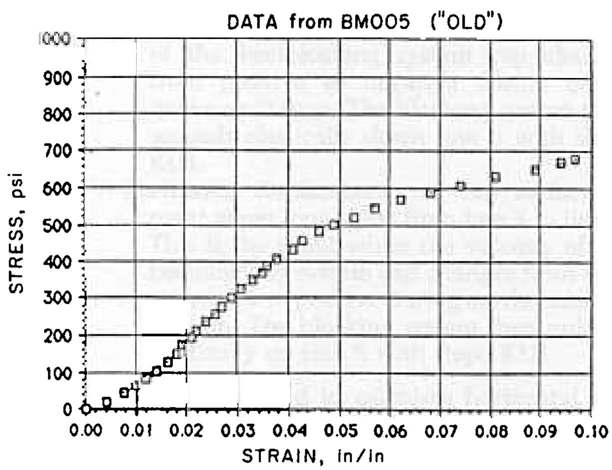

Fig. 6 Stress-strain curve for old Douglas fir timbers. At 500 psi, apparent MOE = 10 492 psi; FSPL = 411 psi; MOE = 12 945 psi

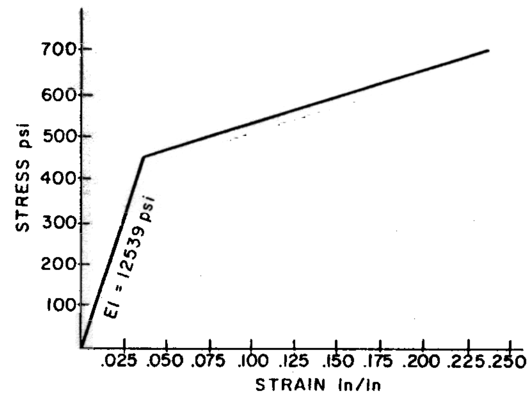

Fig. 7 Idealized stress-strain curve, Douglas fir; side block vertical loading

measuring the slopes off this figure are $E1$ = 12 539 psi and $E2$ = 3474 psi. From these values an idealized stress-strain curve for Douglas fir in the side blocks subject to vertical loading is constructed. This is illustrated in Fig. 7. For horizontal loading, grain orientation has a very large effect. In this case, the perpendicular values of $E1$ and $E2$ are multiplied by a factor of 7.6 obtained from Panshin's Fig. 6.8 [11] to obtain the horizontal values $E1$ = 95 297 psi and $E2$ = 26 398 psi.

In the case of Douglas fir in the keelblocks, the horizontal applied force is exactly parallel to the grain. This results in values of $E1$ = 175 549 psi and $E2$ = 48 629 psi. Oak is assumed to stay linear. Oak is generally stiffer and the Douglas fir cap areas are smaller and thus subject to higher stresses. The modulus of elasticity value used in all cases for vertical loads on oak is 23 980 psi obtained from blocking material test data [12]. For horizontal loads the modulus value for oak for keelblocks and side blocks is 335 720 psi. Cap angle is assumed to not affect the oak. The oak layer is assumed to be perpendicular to the vertical loads and parallel to the horizontal loads.

Sigman [6] assumed in his research that the submarine drydock blocking systems failed when the Douglas fir caps were loaded beyond their FSPL. This is an unnecessarily restrictive assumption that does not allow taking into account the hysteretic damping effects produced by wood when it deforms plastically. The Douglas fir caps actually remain intact up to a stress beyond 700 psi. This is well beyond the assumed FSPL of 450 psi.

If the blocks are assumed to survive past the FSPL, a new way of modeling the block stiffness other than linear elastic needs to be developed. One way of modeling this behavior, called elasto-plastic, is described by Biggs [13] and Paz [14]. This model assumes that after the material is loaded past its proportional limit, it becomes purely plastic with stiffness equal to zero. The material unloads with exactly the same slope (stiffness) as it is loaded. This elasto-plastic model is fairly close to the behavior of wood; however, the stiffness of the Douglas fir in the keelblock system does not go to zero past the FSPL. Therefore, the elasto-plastic model must be modified to more closely match the behavior of the Douglas fir.

A curve which matches the behavior of Douglas fir more closely is that shown in Fig. 8. This behavior is called bilinear. This figure is an illustration of this model as applied to the horizontal keel blocking system. The entire keelblocking system is assumed to exhibit bilinear behavior. However, all the materials in the keelblocking system

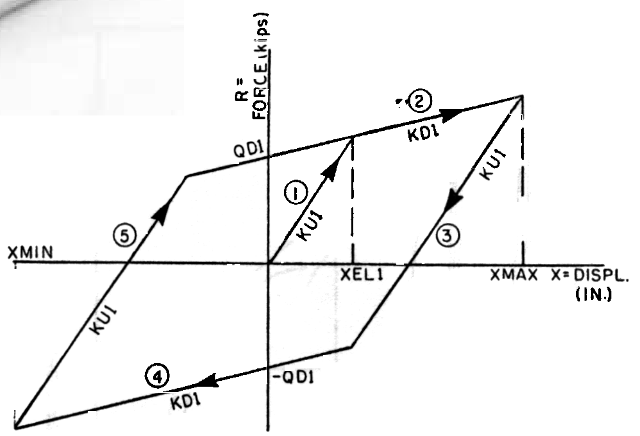

Fig. 8 Bilinear force/displacement curve for horizontal keelblocking system

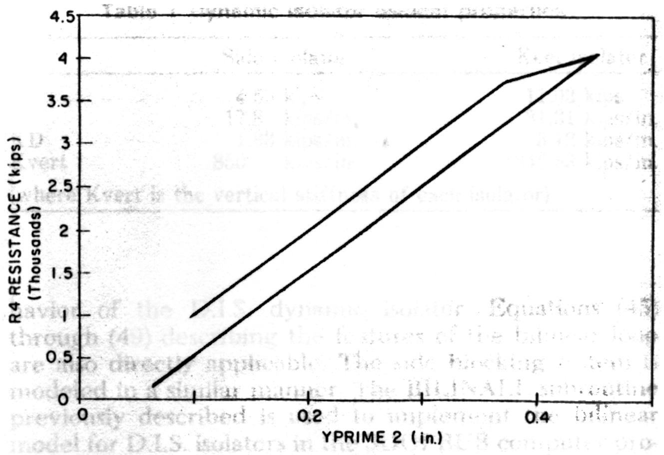

Fig. 9 System No. 1 bilinear YPRIME 2 versus R4, 15 percent of 1940 El Centro earthquake

are assumed to remain linear-elastic except the Douglas fir, which changes its modulus of elasticity once its FSPL is exceeded. . . . In Fig. 8, KU_1 is the initial elastic stiffness value and KD1 is the stiffness after the systems has been loaded past FSPL. The following equations describe the various features of the bilinear loop in Fig. 8:

$$XEL1 = P/khk = \sigma_s A_s/khk \quad (43)$$
$$QD1 = XEL1\,(KU1 - KD1) \quad (44)$$
$$\text{Line 1: } R = KU1 \times x \quad (45)$$
$$\text{Line 2: } R = KD1 \times x + QD1 \quad (46)$$
$$\text{Line 3: } R = KU1 \times x + (KD1 - KU1) \times XMAX + QD1 \quad (47)$$
$$\text{Line 4: } R = KD1 \times x - QD1 \quad (48)$$
$$\text{Line 5: } R = KU1 \times x + (KD1 - KU1) \times XMIN - QD1 \quad (49)$$

where

- XEL1 = elastic limit for blocking system, in.
- σ_s = maximum shear stress parallel to grain for Douglas fir
- A_s = keelblocking system cap area
- R = restoring force of keelblocking system due to horizontal deformation
- x = horizontal displacement of cap surface of keelblocking system
- XMAX = horizontal displacement of cap surface at point when bilinear loop shifts from line 2 to line 3. This is the point when the velocity of the keelblocking system cap changes from positive to negative during earthquake excitation. The blocking system then unloads elastically down line 3 with slope KU1.
- XMIN = horizontal displacement of cap surface at point when loop shifts from line 4 to line 5. This is the point when the velocity of the keelblocking system cap changes from negative back to positive during earthquake excitation. The blocking system then unloads elastically up line 5 with slope KU1.

A similar procedure is used to calculate horizontal and vertical keel and side block system stiffnesses for all eleven submarine drydock blocking systems studied.

The area inside the bilinear loop is the energy lost to the system due to hysteretic damping during one excitation cycle. Figure 8 is an idealized picture of what would occur during one cycle of earthquake excitation. The BILINALL subroutine incorporated in 3DOFRUB generates bilinear stiffnesses for any point in time during system excitation. If plastic deformation of the side blocks occurs, the Douglas fir caps incur a permanent set. The 3DOFRUB program produces output, as shown by Fig. 9. Failure occurs earlier because the location of the actual side block surface has changed. Liftoff would occur at this new lower position.

Figure 10 is typical of the bilinear behavior due to horizontal loading of the keel or side blocks due to earthquake loading. One of the features of the bilinear subroutine logic is that as the velocity of the earthquake suddenly changes and the amplitudes decrease for a short period, the curve oscillates along an elastic line. Many of these oscillations can be seen in Fig. 10. This response is considered reasonable and is confirmed by experimental results derived for dynamic isolators as shown in Fig. 11 [15].

Determination of dynamic isolator blocking properties

The use of dynamic isolators in drydock blocking systems offers many advantages over standard drydock blocking configurations used today in high seismic risk areas. Dynamic isolators decouple the drydocked submarine from horizontal ground accelerations, dissipate earthquake energy, and significantly reduce accelerations seen by deli-

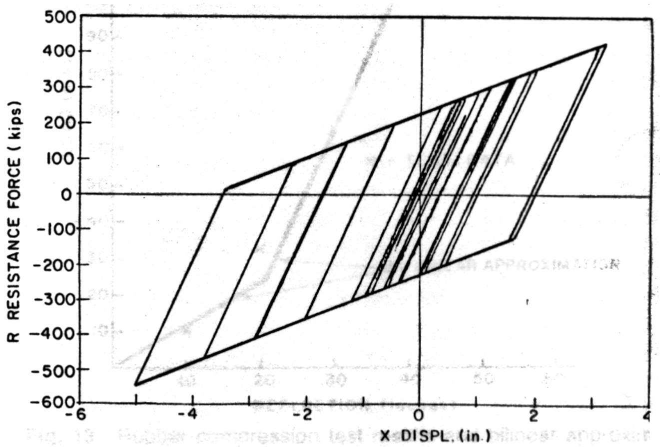

Fig. 10 Bilinear response, 1940 El Centro quake, system No. 1

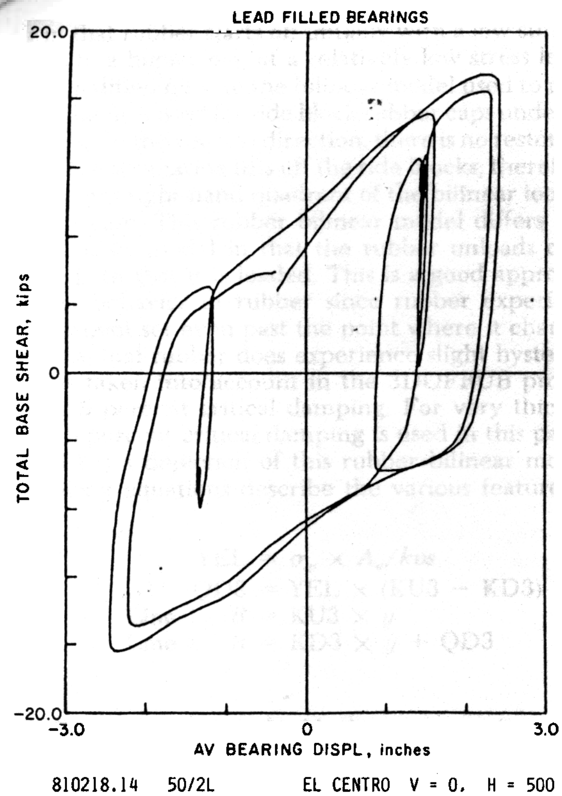

Fig. 11 Lead-filled bearings hysteresis curve from experiments

cate equipment inside the submarine. Figure 12 is an illustration of Dynamic Isolation Systems Inc.'s (D.I.S.) [16] dynamic isolator analyzed in this paper.

Table 1 lists dynamic isolator bilinear properties supplied by D.I.S. for each side block and keelblock isolator. Dynamic isolators exhibit bilinear properties similar to wood described previously. These isolators are of sufficient size and strength to be applicable to submarine drydock blocking system 1.

In order to incorporate these isolator properties into blocking pier stiffness calculations, it is necessary to calculate equivalent elastic moduli for these isolators. For these calculations, four blocking layers are maintained. The isolator replaces the oak layer. It is assumed that the isolator has the same dimensions as the oak.

Figure 8, the bilinear force-displacement curve for the horizontal keelblocking system, is a description of the be-

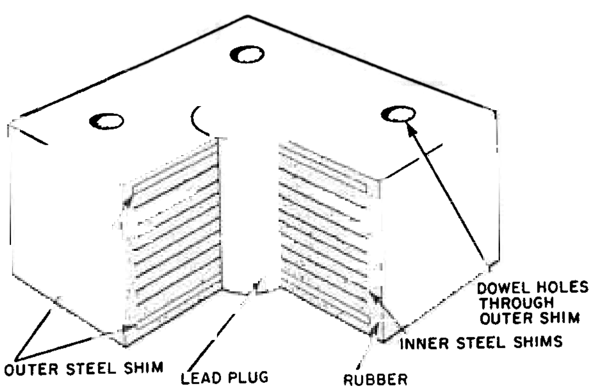

Fig. 12 The D.I.S. lead-rubber bearing

Table 1 Dynamic isolator bilinear properties

	Side Isolator	Keel Isolator
QD	4.55 kips	11.03 kips
KU	17.8 kips/in.	31.31 kips/in.
KD	1.83 kips/in.	3.72 kips/in.
Kvert	850 kips/in.	1845.83 kips/in.

(where Kvert is the vertical stiffness of each isolator)

havior of the D.I.S. dynamic isolator. Equations (45) through (49) describing the features of the bilinear loop are also directly applicable. The side blocking system is modeled in a similar manner. The BILINALL subroutine previously described is used to implement the bilinear model for D.I.S. isolators in the 3DOFRUB computer program.

Determination of rubber cap properties

Rubber has many properties that make it an ideal capping material for drydock blocking systems. Though rubber is a nonlinear material, it is possible to model it as a bilinear material using procedures similar to those for wood. Based on data from compression tests conducted by the Johnson Rubber Company[6] on natural rubber, a bilinear model is developed. These test results are shown in Fig. 13. Two lines are drawn on Fig. 13 to approximate the nonlinear load deflection behavior measured. From these lines two values of bilinear modulus of elasticity are computed.

Using the two computed moduli and the yield stress for natural rubber, an idealized stress-strain curve for natural rubber for side block vertical loading is constructed. This differs from the idealized stress-strain curve for Douglas

[6] Private communication with T. Blackie, chief engineer, Duramax Marine Div., Johnson Rubber Co., Middlefield, Ohio, Jan. 1988.

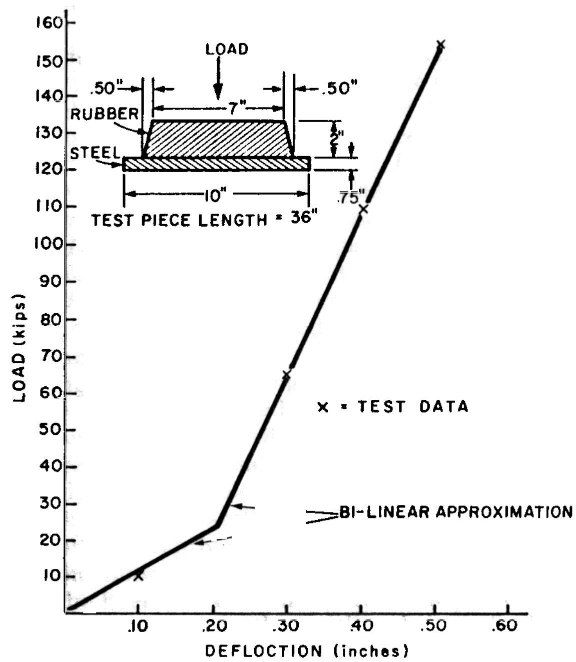

Fig. 13 Rubber compression test results and bilinear approximation (from Johnson Rubber Co.)

fir in that rubber starts off initially with a low stiffness and shifts to a higher one at a relatively low stress level.

A modified form of the bilinear model used to represent Douglas fir is used for side block rubber caps under vertical loading. In the vertical direction, there is no restoring force once the submarine lifts off the side blocks; therefore, only the upper right-hand quadrant of the bilinear loop is valid in this case. This rubber bilinear model differs from the Douglas fir model in that the rubber unloads down the same path that it is loaded. This is a good approximation of the behavior of rubber since rubber experiences no permanent set even past the point where it changes stiffness. Actual rubber does experience slight hysteresis, but this is taken into account in the 3DOFRUB program by using 5 percent critical damping. For very thick rubber caps 8 percent critical damping is used in this paper. Figure 14 is a depiction of this rubber bilinear model. The following equations describe the various features of Fig. 14:

$$\text{YEL} = \sigma_v \times A_c / kvs \tag{50}$$

$$\text{QD3} = \text{YEL} \times (\text{KU3} - \text{KD3}) \tag{51}$$

$$\text{Line 1:} \quad R = \text{KU3} \times y \tag{52}$$

$$\text{Line 2:} \quad R = \text{KD3} \times y + \text{QD3} \tag{53}$$

where

YEL = elastic limit for blocking system, in.
A_c = cap area for one set of side blocks
R = restoring force of side blocking system due to vertical displacement
σ_v = vertical displacement of cap surface of side blocking system
QD3 = R intercept of second stiffness slope

Since natural rubber exhibits bilinear behavior at a very low stress level, it is necessary to also develop a bilinear model for the keelblocks. An additional subroutine, RUBBER, for the 3DOFRUB computer program, is developed to include the rubber bilinear behavior.

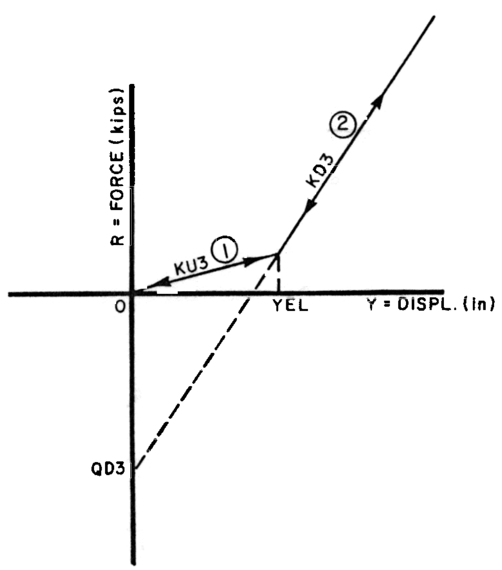

Fig. 14 Bilinear force/displacement curve, rubber caps; side blocks vertically loaded

Fig. 15 USS *Leahy* side block No. 14 (official U.S. Navy photograph, 1 Oct. 1987, Long Beach Naval Shipyard)

USS *Leahy* (CG-16) case study

Background

On October 1, 1987, while in graving dock No. 3 at Long Beach Naval Shipyard (LBNSY), Long Beach, California, the USS *Leahy* (CG-16) experienced an earthquake. The 5.9-magnitude (0.45 *g* maximum peak acceleration) earthquake had an epicenter located 20 miles to the northeast in Whittier, California [17]. The ship experienced side block sliding, and photographs of the drydock blocking system showing the block displacements were taken immediately after the earthquake. In addition, dry docks at LBNSY had been instrumented by accelerographs which recorded the drydock accelerations (0.05 *g* peak) seen by the *Leahy* during the earthquake. Because of the recorded displacement and acceleration time histories, the USS *Leahy* was an outstanding case to analyze in order to verify the three-degrees-of-freedom model and the 3DOFRUB computer program.

Figure 15 is a photograph of the No. 14 (second most forward) starboard side block. This photograph clearly shows the outboard displacement of the block. These displacements were measured and recorded. There was no evidence of side block or keelblock crushing or keelblock sliding. There was slight evidence of side block liftoff. This liftoff apparently slightly skewed some of the side blocks so the inboard face of the side blocks was no longer parallel to the keel line. In addition, the new paint that had been applied just before the earthquake was broken between the hull and block interface. Figure 15 is an excellent illustration of side block buildup angle alpha (α) and side block cap angle beta (β).

The dry docks at LBNSY are some of the only dry docks in the world instrumented with accelerographic equipment. These instruments were installed by the Naval Facilities Engineering Command and monitored by the Naval Civil Engineering Laboratory, Port Hueneme, California. When the October 1, 1987 earthquake occurred, all of the accelerographs were triggered in the dry docks at LBNSY. The acceleration time histories were recorded on film in these instruments.

The closest accelerograph to the USS *Leahy* during this earthquake was located in dry dock No. 2 which is approximately 500 ft to the east of where the ship was drydocked. Dry dock No. 2 is virtually identical in size and construction to dry dock No. 3 where the *Leahy* was located.

The characteristics of the USS *Leahy's* drydock blocking system were obtained from the docking officer. The information used came from a "layout sheet" which was used to construct the blocking system. The following information is obtained from this sheet and is used in producing an input data file for the 3DOFRUB computer program:

Side block height (htside)
Keelblock height (htkeel)
Numbers of blocks
Side block cap angles (beta)
Side block breadths (br)

The moment of inertia about the keel for the *Leahy* is calculated using a formula given by Gillmer and Johnson [18] based on the ship's beam for a destroyer-type ship. The ship is modeled as a "rigid body." Since each set of *Leahy's* side blocks has different heights, the *Leahy* system is modeled several times using each set's heights.

One of the most interesting results found in examination of the *Leahy's* blocking system is that the outboard displacement varied significantly from block to block. Figure 16 is a plot of measured outboard block displacement versus cap angle. This figure shows that as cap angle increases, outboard side block displacement increases in a linear fashion.

This type of behavior is consistent with the side block sliding analysis incorporated in the 3DOFRUB computer program. Once sliding occurs, however, the three-degrees-of-freedom model used in 3DOFRUB breaks down. There is no means incorporated into the program to determine the amount of side block displacement.

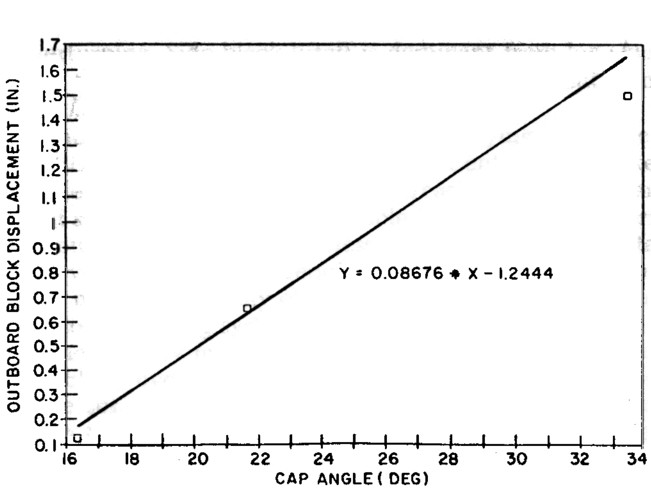

Fig. 16 USS *Leahy* (CG-16) during 1 Oct. 1987 quake, measured block displacement outboard

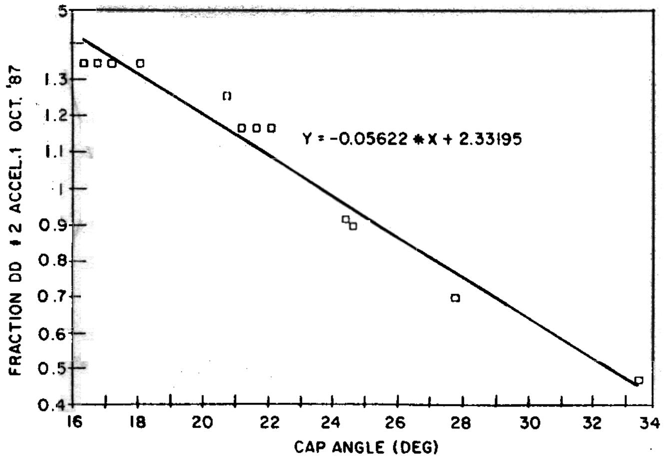

Fig. 17 USS *Leahy* (CG-16) during 1 Oct. 1987 quake, fraction acceleration at failure versus cap angle

The next analysis step is to run 3DOFRUB using each side block cap angle in the *Leahy's* blocking system. A relationship is found as seen in Fig. 17 between cap angle and the system's survivability when subject to the horizontal and vertical dry dock No. 2 acceleration time histories.

Since block-on-block surfaces for this system had probably been painted, the friction coefficient of 0.3 [19] is assumed. Figure 17 shows a linear relationship between earthquake survivability and cap angle. As cap angle increases, the system's survivability decreases due to side block sliding.

Figure 17 predicts that the following side blocks would slide when subject to the dry dock No. 2 acceleration time history: 15, 14, 13, 7, 12, 6, 1, 4. All of these blocks were observed to slide. The program predicts failure ranging from 47 to 117 percent of the dry dock No. 2 acceleration time history. The side block systems which are predicted to fail at the lowest acceleration time histories were those side blocks with the highest cap angles. This correlates very well with observed side block sliding failures on the USS *Leahy*.

The model predicts side block sliding failure as the primary failure mode for the USS *Leahy* system subject to the dry dock No. 2 acceleration time history. This is precisely the actual system failure observed. The model also predicts that side block liftoff is the primary failure for side blocks with small cap angles. Again, this is consistent with observations of the side blocks. Based on these results, the three-degrees-of-freedom model and the 3DOFRUB computer program appear to correctly reflect the behavior of an actual drydock blocking system, including the effects of side block geometry.

Wale shore, isolator, and block stiffness/ geometry variation parametric studies

Parametric study description

It has already been seen that present U.S. Navy drydock blocking systems are inadequate to resist expected earthquake accelerations. Some potential new materials such as rubber caps and dynamic isolators look promising in correcting this problem. Many other design improvements, including the use of wale shores, stiffening the side blocks, and widening the blocking system base, show po-

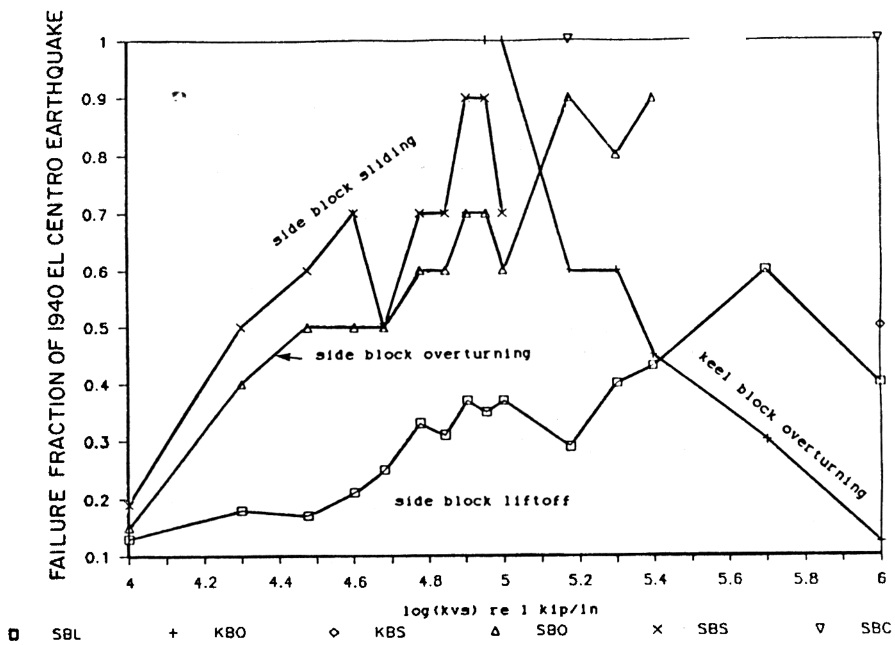

Fig. 18 Side block vertical stiffness versus failure: Ksh = 100 000 kips/in., all modes

tential. In order to explore these possibilities and establish a feel for the design space, a series of parametric studies using the 3DOFRUB computer program is conducted.

In order to determine the design space, wale shore stiffness and side block and keelblock horizontal and vertical stiffnesses inputs to 3DOFRUB are varied. Submarine drydock blocking system No. 1 is used as a baseline for these studies. The 1940 El Centro earthquake acceleration time history is used throughout this parametric study. For several of these studies, the effect of doubling the keelblock widths is investigated.

The results of system No. 1 vertical side block stiffness variations is shown in Fig. 18. Log (kvs) with respect to 1 kip/in. is plotted against failure fraction of the earthquake. For each stiffness, failure fractions due to all failure modes present are plotted. The primary failure modes for this system are side block liftoff, keelblock overturning, side block overturning, and side block sliding.

Since all failure modes are shown in Fig. 18, their relative dominance can be seen. The modes of failure which dominate this system are side block liftoff and keelblock overturning. Side block liftoff is dominant from log (kvs) = 4 to 5.4, and keelblock overturning is dominant from log (kvs) = 5.4 to 6.

The best survivability attained by varying side block vertical stiffness is 40 percent of the El Centro earthquake. While there is some promise in increasing side block vertical stiffness, it is still not possible to meet the 0.2 g criterion by increasing this stiffness alone. Also, the horizontal and vertical stiffnesses required are extremely high and may not be practically obtainable in an actual submarine drydock blocking system.

Another key factor evident in Fig. 18 is that side and keelblock overturning are important issues. As stiffness increases, side block overturning and sliding become less important; however, above 100 000 kips/in., keelblock overturning quickly becomes increasingly important until it dominates. It is clear that any design strategy must take into account both preventing side block liftoff and keelblock overturning. As one failure mode is eliminated, another will come to dominate; therefore, a design strategy that overcomes the various failure modes at the same time is required.

Results of using wale shores of various stiffnesses on system No. 1 survivability are shown in Fig. 19. Rapid improvements in system survivability occur as wale shore stiffness is increased. To prevent the occurrence of keelblock overturning, double-width keelblocks are used in this study.

As seen in Fig. 19, the three primary failure modes are side block liftoff, keelblock overturning, and keelblock sliding. Side block liftoff is dominant up to log(ks) = 4.4. Keelblock overturning overtook side block liftoff and dominates failure for log(ks) = 4.6 and above. The best survivability seen is 60 percent of the El Centro earthquake, which is well above the 0.2 g criteria. Therefore, the use of wale shores is quite promising, and the required stiffness appears obtainable.

The use of wale shores increases system survivability by preventing the rotation and horizontal displacement of the submarine during the earthquake. This is due to the large restoring moment provided by the wale shores resulting from their high position above the keel baseline. Wale shores also shift the horizontal and rotational system modal frequencies well above the excitation frequencies of the earthquake.

When the side and keelblocks are prevented from overturning and 1 in. of rubber is added to the block caps, extremely high system survivability can be obtained using wale shores. It is found that the use of 1-in. rubber caps alone more than doubled system survivability. This is due to the rubber cap delaying side block liftoff. The wale shore stiffness is then varied up to the optimum stiffness values, 30 000 kips/in., shown in Fig. 19.

By increasing the wale shore stiffnesses, survivability increased quickly up to about 80 percent of the El Centro earthquake. After this magnitude of earthquake, increasing wale shore stiffness gave diminishing returns. This study indicates that wale shores are a viable solution to the submarine drydock blocking survivability problem.

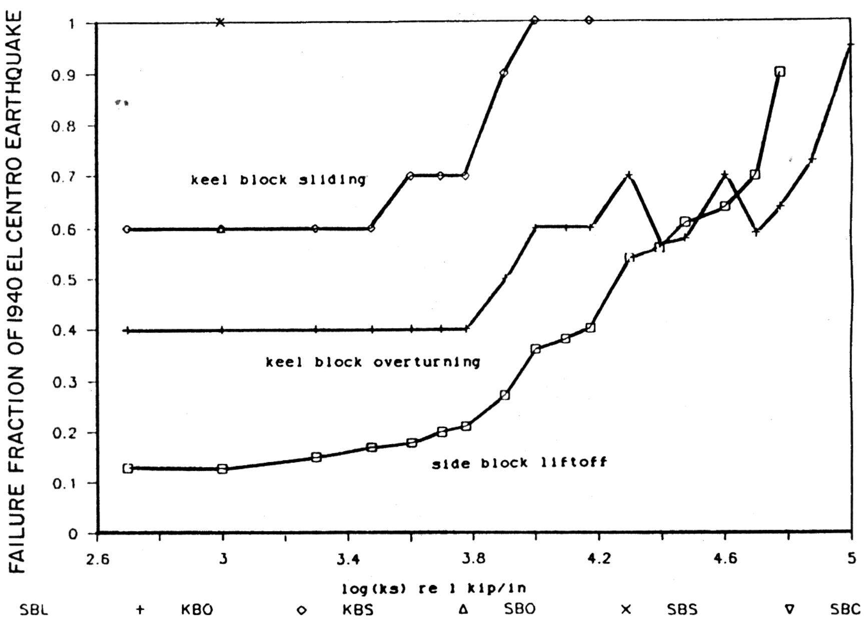

Fig. 19 Wale shore stiffness versus failure, wale shores and double keelblocks

Drydock blocking system survival comparisons and site-specific effects

Overall comparison among bilinear wood, bilinear rubber, isolators, and Sigman results

Figure 20 combines the results for the eleven submarine drydock blocking systems using the various blocking material models. In every material model for all eleven systems, failure is due to side block liftoff. Roughly, this figure shows that the use of rubber as a capping material increases the systems' survivability, and the use of the bilinear model decreases the survivability from the model used by Sigman.

Figure 21 is the comparison of the survival percentage of system No. 1 using Sigman's model, the bilinear wood model, the bilinear rubber model, and the bilinear D.I.S. isolator model described previously. The rubber caps and isolators each approximately double the system's survivability. This figure clearly indicates the potential use of rubber caps and/or dynamic isolators.

Figure 22 is a plot comparing the survivability of eleven bilinear wood submarine systems with the linear wood systems. In this comparison there is a clear difference in survivability between the two studies. Overall, linear systems survive a higher earthquake percentage (26 percent) than bilinear systems (23 percent). There is no case where the bilinear systems survive a larger earthquake than the linear systems. In most cases the cap does plastically deform, causing the Douglas fir to incur permanent set and thus earlier side block liftoff. This comparison shows that

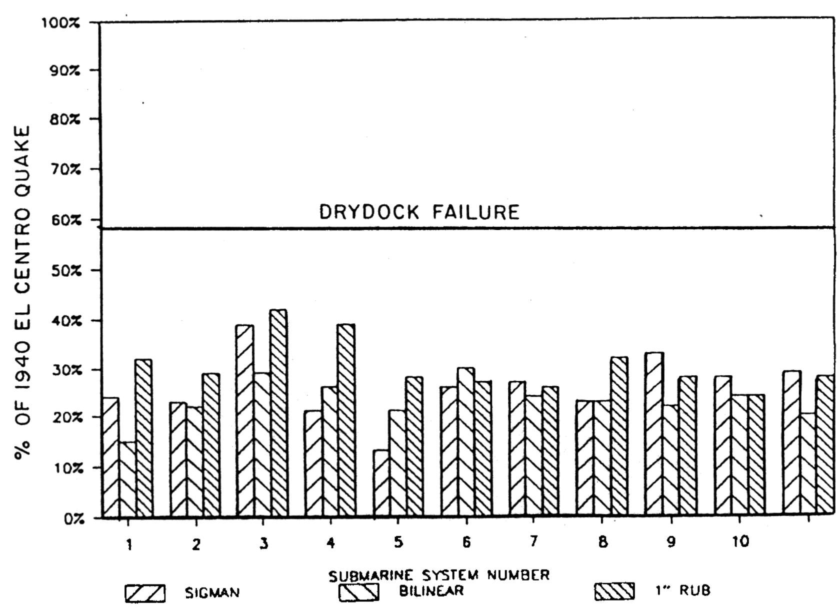

Fig. 20 Submarine blocking systems (1-11) survival percentage comparisons

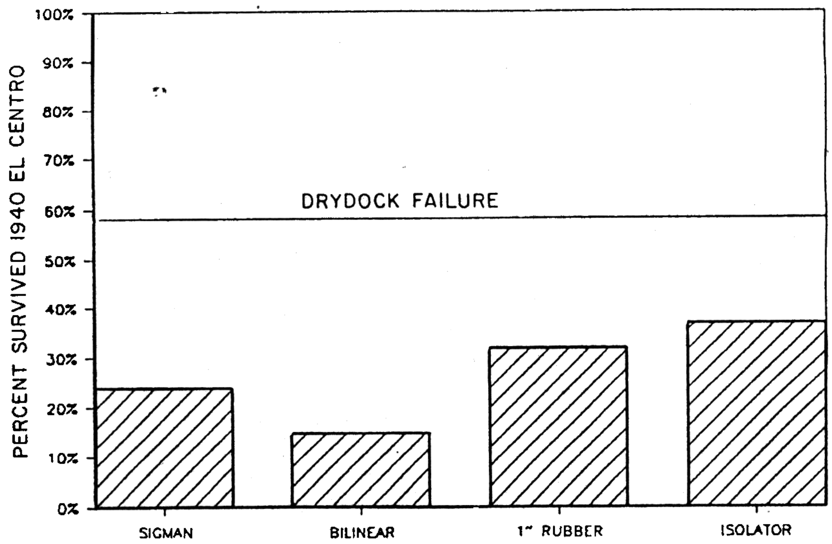

Fig. 21 Submarine drydock blocking system No. 1 material comparison

the bilinear analysis was more conservative by approximately 10 percent.

Earthquake site specificity

Earthquakes differ widely in magnitude, frequency, and duration. Their effect on local structures is also dependent on the immediate geological characteristics of the surrounding area. For this reason, using the 1940 El Centro earthquake acceleration time history alone is not considered adequate to develop a satisfactory submarine drydock blocking system design.

In the case of the October 1, 1987 Whittier earthquake, measured ground acceleration varied tremendously depending on the distance and direction from the epicenter. The frequency spectrum of the recorded ground accelerations also depends on local geological conditions [17].[7]

[7] Private communication with T. K. Lew, Structures Div., Naval Civil Engineering Laboratory, Port Hueneme, Calif., Jan./Feb. 1988.

Dry dock No. 2 at Long Beach Naval Shipyard, where accelerations were measured, is located approximately 20 miles from the epicenter of the Whittier earthquake (footnote 7). The ground acceleration was reduced from 0.45 g's peak acceleration near the epicenter to 0.052 g's peak in dry dock No. 2. In addition, the dominant frequency of the earthquake was reduced from approximately 2 Hz near the epicenter to near 1 Hz in dry dock No. 2.

Lew (footnote 7) stated that dry dock No. 2 is sitting on an aquifer which exhibits dynamic characteristics similar to a solid. Along the sides of the dry dock is a layer of solid material rising approximately 10 ft above the aquifer. A 30-ft-deep hydraulic layer exists above this solid material. Above this is a compacted landfill layer. This combination of geological properties around the dry dock contributes to the relatively low ground acceleration frequencies experienced.

The geological conditions which exist at Long Beach Naval Shipyard are very similar to conditions at other graving dock locations. Lew (footnote 7) also stated that

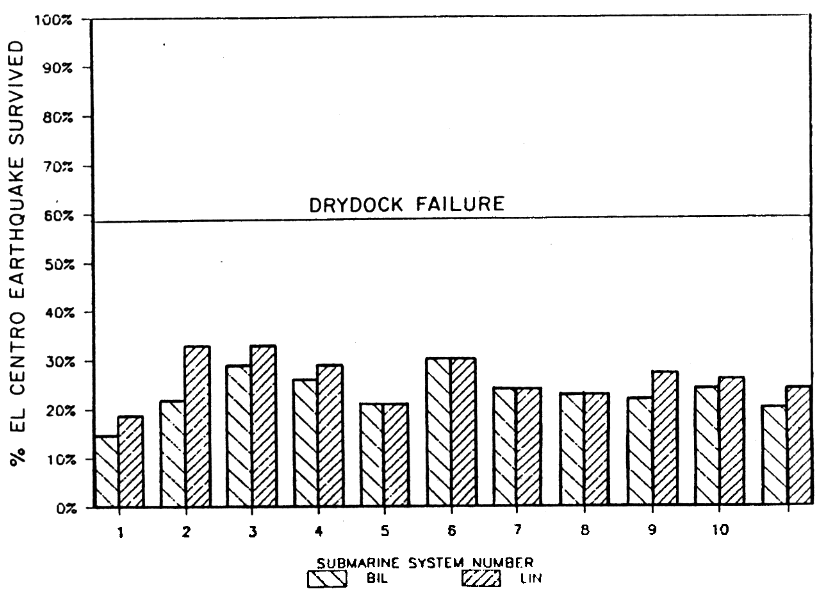

Fig. 22 Survival percentage comparisons, bilinear versus linear

Mare Island Naval Shipyard can withstand a maximum of 0.26 *g*'s before the construction joints of the dry dock give way. This value is used as the "dry dock failure" level in this paper. Lew stated that the dry docks at Long Beach probably have the same design limitation. The dry docks at both these locations are very similar in construction.

For dry dock No. 2 acceleration time histories, both the vertical and horizontal components were available. These two time histories differ substantially in magnitude and frequency content. In order to make a valid comparison between the effects of using the 1940 El Centro earthquake and the dry dock No. 2 acceleration time histories, the dry dock's accelerations are normalized to the El Centro's magnitudes. The energy content of an earthquake depends on the magnitude of its ground displacements and the earthquake duration [20]. The amount of energy that an earthquake imparts to a structural system depends on the earthquake's frequency content relative to the natural frequencies of the structure. The dry dock No. 2 accelerations are normalized to the same magnitude as El Centro by multiplying by a factor of 10.97, which is a ratio of the earthquake's peak displacements.

Figure 23 shows the 1940 El Centro earthquake acceleration time history and the normalized dry dock No. 2 acceleration time history. It is clear from these plots that the excitation frequency of the normalized earthquake is much lower than that of the El Centro. These two earthquake acceleration time histories are used in this paper for system design development.

It is clear from previous analysis that both a low-stiffness design approach using isolators and a high-stiffness design approach using wale shores are both viable. Using a higher-frequency earthquake like the El Centro is a more conservative approach for a high stiffness design. Similarly, a lower-frequency earthquake like the normalized dry dock No. 2 accelerations is a more conservative approach for a low-stiffness design. El Centro's dominant frequency is approximately 2 Hz for the 5 percent damping case used in this paper. For dry dock No. 2 this dominant frequency is approximately 1 Hz, again using 5 percent damping.

To determine the dependence of system survivability on system natural frequency, a plot is made, Fig. 24, show-

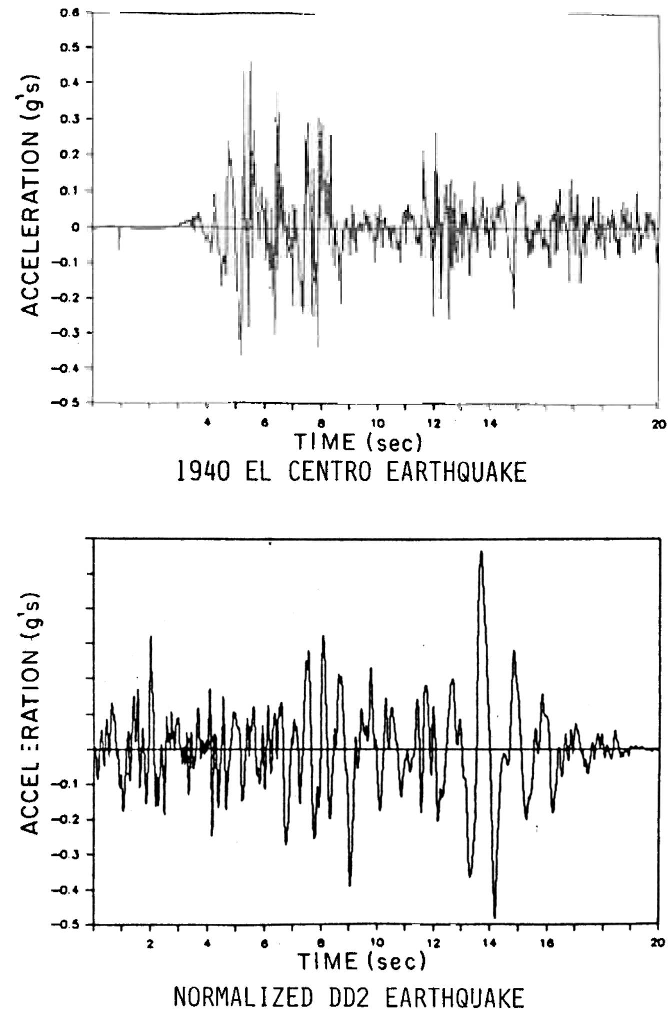

Fig. 23 Acceleration time history comparison

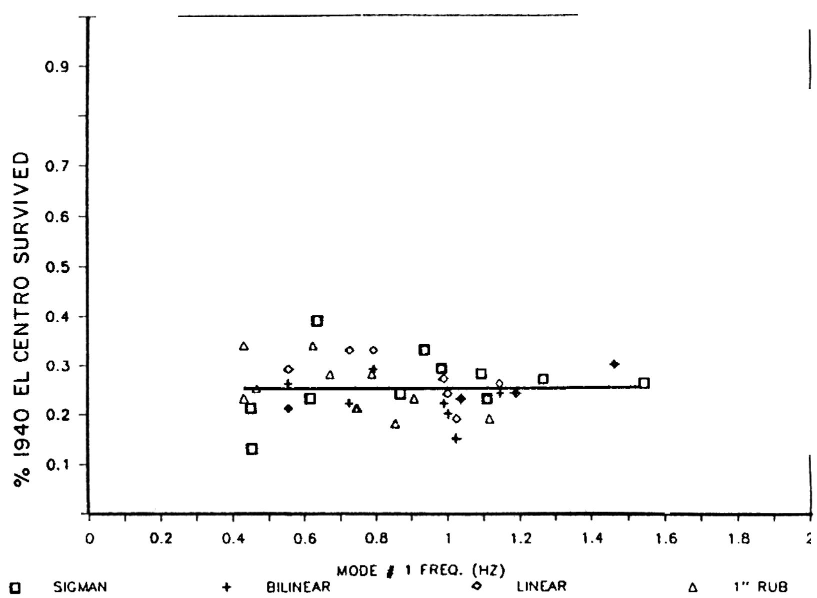

Fig. 24 Percentage failure versus Mode 1 frequency (Hz), includes Sigman, bilinear, linear, and 1-in. rubber

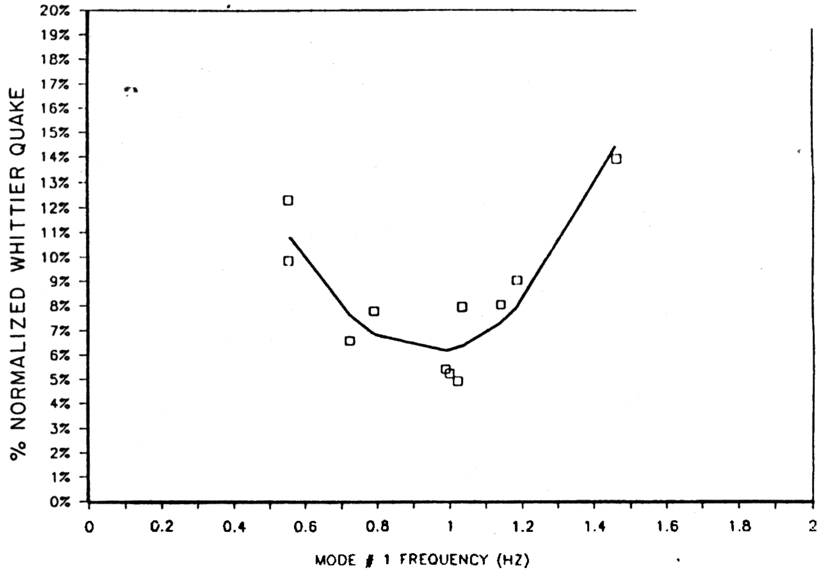

Fig. 25 Percentage survived versus Mode 1 frequency, normalized Whittier (DD2) quake

ing El Centro earthquake survivability versus Mode 1 frequency. All eleven systems' Mode 1 frequencies using Sigman's, bilinear, linear, and 1-in. rubber cap models are plotted. The natural frequencies for these systems range from 0.4 to 1.6 Hz with an average around 1 Hz.

There is no correlation between Mode 1 frequency and earthquake survivability for these systems as shown by the data and the flat best-fit line. This is because the Mode 1 frequency, the lowest system modal frequency, is sufficiently below the dominant frequency of the El Centro earthquake, 2 Hz. No dynamic amplification occurs. Significant dynamic amplification and thus lowered survivability is expected if the system modal frequency is near the earthquake's dominant frequency.

This is precisely what is found when eleven bilinear systems are excited by the normalized dry dock No. 2 earthquake. Figure 25 is a plot of normalized dry dock No. 2 earthquake survivability versus Mode 1 frequency. In this case, the dominant frequency of the earthquake, 1 Hz, corresponds to the average system modal frequency. A clear dependence of system survivability on frequency is shown in the figure by the best-fit curve. The systems with natural frequencies closest to that of the normalized dry dock No. 2 earthquake have the lowest survivability.

A comparison of the survivability of the eleven submarine drydock blocking systems due to El Centro and normalized dry dock No. 2 earthquakes is shown in Fig. 26. This figure clearly illustrates the degradation of system survivability due to resonant frequency effects. All eleven systems fail at much lower levels when excited by the lower-frequency normalized dry dock No. 2 earthquake. Overall, system survivability is about 8 percent for the normalized dry dock No. 2 earthquake compared with 23 percent for the El Centro earthquake.

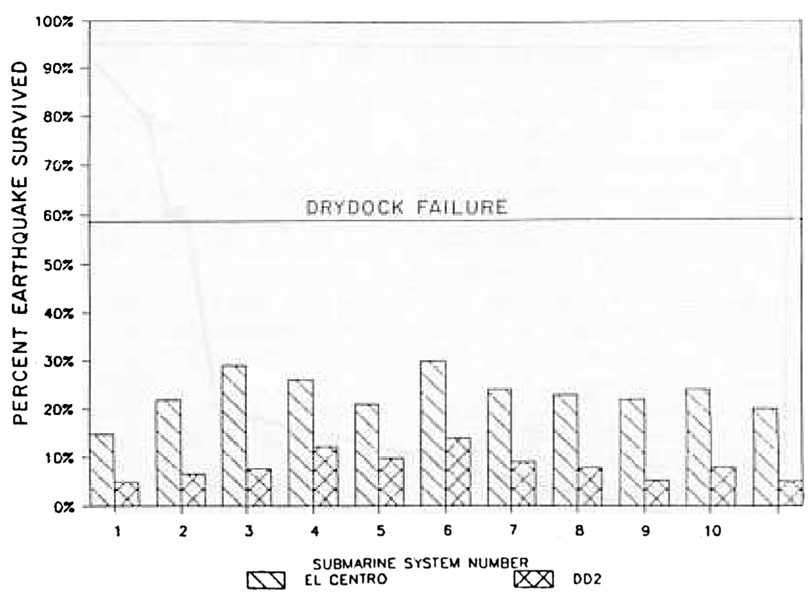

Fig. 26 Bilinear survival percentage comparisons, El Centro versus Normalized DD2

It is important to emphasize that these low survivability percentages for submarine drydock blocking systems are based on an actual earthquake acceleration time history measured in a U.S. naval shipyard dry dock. The validity of this problem is confirmed by the USS *Leahy* case study where a current U.S. Navy ship drydock blocking system failed when subject to a relatively small earthquake (0.05 *g* peak acceleration). This shows the importance of taking frequency dependence into account when designing an earthquake resistant system.

Isolator and rubber low-stiffness design

Design process

Dynamic isolators and rubber caps either singly or in combination are very attractive potential solutions to the submarine drydock blocking system survivability problem. Using the 3DOFRUB program with the BILINALL and RUBBER subroutines, a design study of a blocking system with D.I.S. isolators and rubber caps is undertaken. The purpose of this study is to find a low stiffness system which survives up to dry dock failure (0.26 *g*'s).

The first result is unexpected. Using the D.I.S. isolators without a rubber cap, it was found that the system survives 35 percent of the earthquake. With 1-in. rubber caps without isolators, system No. 1 survives 32 percent. It was expected that the combination would increase survivability. Actually it is found that this combination resulted in lower (20 percent) survivability.

In general, this decrease is due to the effect of multiple modes of vibration. By using either 1-in. rubber caps or D.I.S. isolators singly, the system's Mode 1 frequency is driven well below the fundamental frequency of the El Centro earthquake. At the same time, the system's Mode 2 frequency is driven lower but still remains well above the earthquake's fundamental frequency.

By combining the rubber and isolators, the Mode 1 frequency is driven very low, but the Mode 2 frequency is driven into resonance. From this it became clear that to develop a successful design, both the Mode 1 and Mode 2 system frequencies must be driven well below resonance without driving Mode 3 into resonance. While Modes 1 and 2 are coupled, Mode 1 is primarily the system's rotation, and Mode 2 is primarily horizontal displacement. Mode 3 is the system's vertical displacement.

Several runs are made with progressively fewer horizontally stiff isolators. Figure 27 is plot of the 1-in. rubber cap/isolator system survivability versus Mode 2 frequency. The figure shows that as the system's frequency and horizontal stiffness is decreased, system survivability increases dramatically. The Mode 2 frequency is being driven below the earthquake's fundamental frequency.

Figure 27 shows that the system survives a 0.26 *g* earthquake; however, the horizontal stiffness required is reduced by 60 percent from the original rubber/isolator horizontal stiffness. To actually construct a system with this horizontal stiffness would require isolators with extremely low horizontal stiffness. These isolators may be impractical to fabricate.

To allow the isolators to have higher horizontal stiffness the effects of using thicker rubber caps is explored. Six inches is considered the practical thickness limit. Rubber caps thicker than this would tend to be vulnerable to wind loads, and the wind load problem is not investigated in this paper.

The use of 6 in. of rubber significantly shifts the survivability curve to the right. Therefore, 6 in. is selected for the final low-stiffness design solution. Figure 28 is a comparison between the various rubber cap thicknesses for a given horizontal stiffness. This shows the additional benefits of the use of rubber caps. Increasing the thickness of the rubber improves survivability by preventing liftoff.

The use of at least 1 in. of rubber cap is vital. Survivability jumps from 5 to 70 percent with the use of just 1 in. of rubber. The side block horizontal stiffness used for the Fig. 28 comparison is the final design stiffness used. The figure shows that if the rubber cap is removed the system would survive a much smaller earthquake than the original system No. 1. However, the rubber caps alone cannot provide a low enough horizontal stiffness to survive up to dry dock failure. The final low-stiffness solution using the 1940 El Centro earthquake survives 72 percent (0.32 *g*'s).

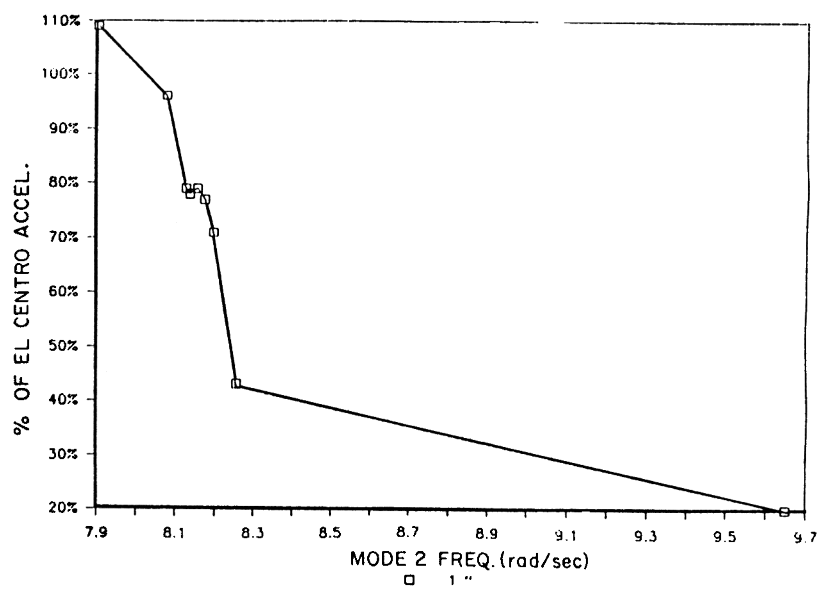

Fig. 27 Percentage survived, 1940 El Centro, for 1-in. rubber caps with isolators

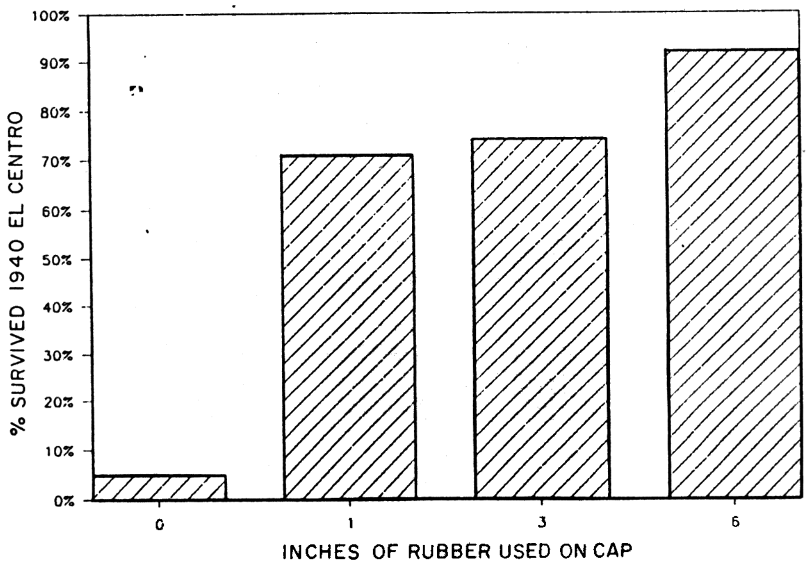

Fig. 28 Effect of using rubber caps and isolators with KHS = 45.5 kips/in.

Since the normalized dry dock No. 2 earthquake has a lower fundamental frequency, this earthquake is used to test the low-stiffness solution. It is found that the horizontal stiffness has to be decreased even further for the system to survive the 0.26 g dry dock survival level. The final survival level is 0.28 g's (63 percent). This new low stiffness solution is recommended if the rubber/isolator method is used. The parameters of the isolators required for this solution are included in Table 2.

The manufacturer (D.I.S.) of the isolators, contacted once the parameters of the required isolators were known, stated[8] that an isolator with these required parameters would be impractical to build. However, he stated that an isolation system of equivalent properties could be built using higher-stiffness isolators on every fourth block.

The blocks without isolators would have low friction sliders which carry the vertical load and provide no horizontal stiffness. These sliders would be coated with a low-friction material such as tetrafluoroethylene (Teflon). Such sliders, according to Buckle, are used extensively in bridge isolation systems. The final low-stiffness solution does incorporate sliders.

Description of the low-stiffness solution

Figure 29 is a 2D drawing of the recommended low-stiffness submarine drydock blocking system solution. This solution survives 63 percent (0.28 g's) of the normalized dry dock No. 2 earthquake. The design includes the following features:

1. Isolators will be placed in every fourth keel and side blocking pier. All other blocking piers will contain sliders.
2. All keelblock and side block piers are rigidly attached to the dry dock floor to prevent overturning.
3. A steel carriage is used to rigidly tie the caps together transversely to prevent sliding. It also ties the system together longitudinally so the isolators provide a restoring force to the entire system.
4. The steel carriage is only rigidly attached to the blocking piers containing isolators. It is free to slide on all other piers.

[8] Private communication with I. G. Buckle, VP for engineering, Dynamic Isolation Systems, Inc., Berkeley, Calif., Feb. 1988.

Table 2 Final low-stiffness design isolator parameters

	Side Isolator	Keel Isolator
XEL	0.285 in.	0.400 in.
QD	0.638 kips	1.15 kips
KU	2.75 kips/in.	3.36 kips/in.
KD	0.51 kips/in.	0.49 kips/in.
Kvert	850 kips/in.	1845.83 kips/in.

5. A 6-in. rubber cap is used on top of the steel carriage to help prevent liftoff and to aid the isolators in decoupling the submarine from ground acceleration.

Wale shore high-stiffness design

Design process

The use of wale shores increases system survivability by reducing the rotation and horizontal displacement of the submarine during the earthquake. Wale shores also shift the horizontal and rotational modal frequencies well above the fundamental frequencies of the earthquake. From the wale shore parametric study, it is found that using wale shores with stiffnesses greater than or equal to 6000 kips/in. along with 1-in. rubber keelblock and side block caps produces system survivability well in excess of dry dock failure. The 72 percent (0.32 g's) survivability level is desirable to give the system a reasonable factor of safety above the 0.26 g dry dock failure level.

The next step in this study is to determine how to practically realize this design. Once the required total stiffness of the wale shores is determined, the actual number and dimensions of the individual wale shores have to be found. The first assumption made is to design the wale shores for Long Beach Naval Shipyard dry dock No. 2, which is a typical U.S. naval shipyard graving dock. This requires the lengths of the wale shores to be approximately 32 ft when supporting a system No. 1 submarine.

Since the wale shores are compression elements vulnerable to buckling, based on Hughes [21], wide flange steel sections are chosen for the wale shores. In order to minimize dry dock production interference and to avoid

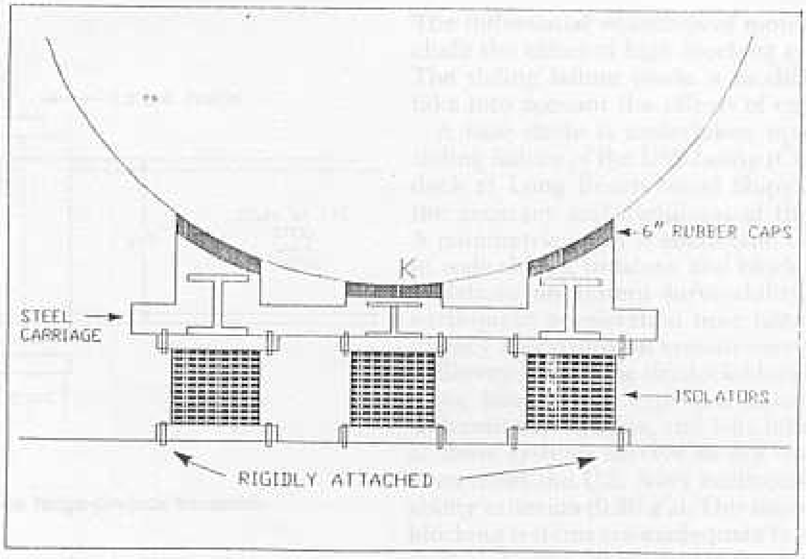

Fig. 29 Isolator and rubber low-stiffness solution

overstressing the submarine, wale shores are placed over existing side block pier locations only. Therefore, the wale shores would bear on the submarine ring stiffeners. To determine the required individual wale stiffness, the number of wale shores is first assumed to be seven. Then a procedure similar to that used to calculate blocking pier vertical stiffness is used to determine what steel section is required to give the necessary overall wale shore stiffness. It is assumed that each wale shore would consist of a layer of rubber, a half-inch steel backing plate, and a wide flange steel beam.

To prevent separation of the wale shore from the submarine during the earthquake the wale shore is initially compressed against the submarine using a hydraulic jack. Once a section is selected, it is tested for buckling survivability. Table 3 lists the parameters obtained for the final high-stiffness wale shore design which satisfies the buckling criteria.

The wale shore is designed so that there is a large enough rubber cap and enough initial compression, F_i, supplied by the jack so that the wale shore never loses contact with

Table 3 Final high-stiffness design wale shore parameters

No. of wale shores	14 per side
Section	27 × 14 WF 145 mild steel
Length	385 in.
σ_{cr}	9095 psi
σ_{ult}	13 500 psi
F_i	138.79 kips

the submarine during maximum horizontal displacement and rotation when the earthquake occurs.

Description of the high-stiffness solution

Figure 30 is a 2D drawing of the recommended high-stiffness submarine drydock blocking system solution. This solution survives 72 percent (0.32 g's) of the 1940 El Centro earthquake and 75 percent (0.34 g's) of the normalized dry dock No. 2 earthquake. The design includes the following features:

1. Fourteen wale shores are placed directly over the side block positions at a position half the diameter of the

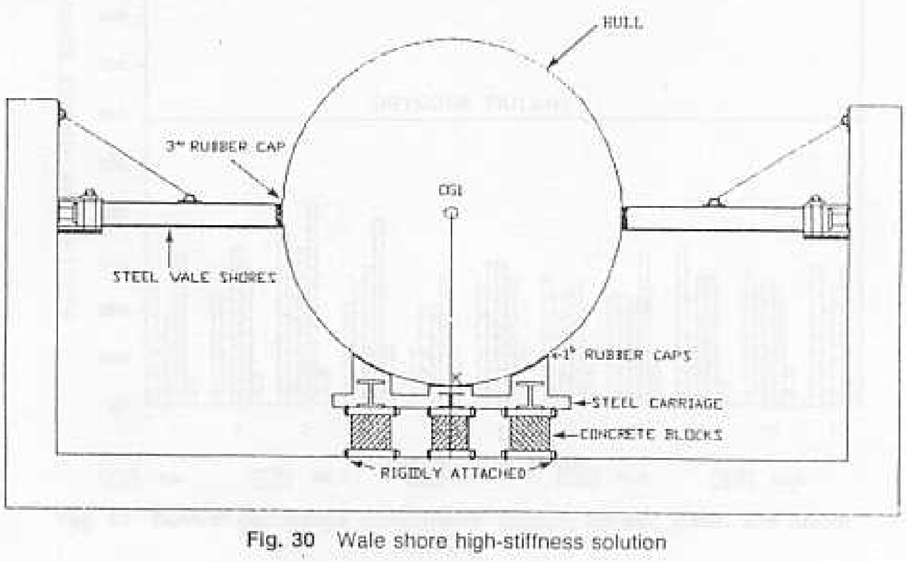

Fig. 30 Wale shore high-stiffness solution

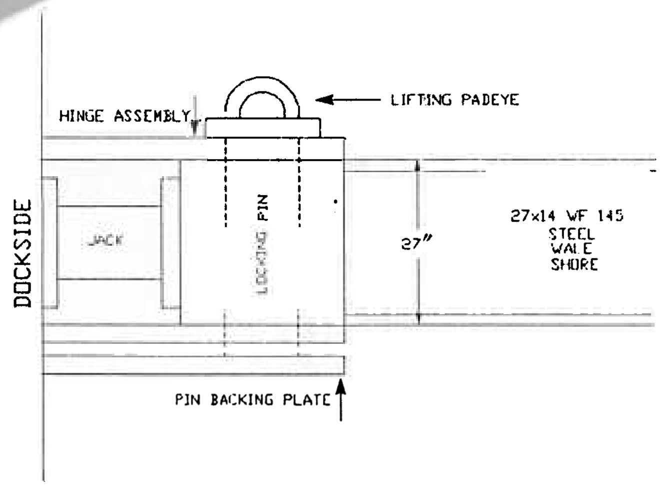

Fig. 31 Dockside hinge-pin-jack assembly

submarine up from the keel. They are attached to the dockside by a hinge-pin-jack assembly as shown in Fig. 31. Cables are used to support and align the wale shores.

2. Each wale shore is 32 ft long. Table 3 describes the steel section used. A 3-in. rubber cap is placed between a backing plate and the submarine hull. A 70-ton jack is used to precompress the wale shore against the submarine to prevent separation during the earthquake.

3. The keel and side concrete blocking piers are rigidly attached to the dry dock floor to prevent overturning.

4. A steel carriage is rigidly attached to the caps and concrete blocking piers to prevent sliding. It also ties the system together longitudinally.

5. A 1-in. rubber cap is used on top of the steel carriage to help prevent liftoff.

Summary, conclusions, and recommendations

This paper describes the development of the three-degrees-of-freedom submarine drydock blocking system design package based on the 3DOFRUB computer program. The differential equations of motion are developed to include the effect of high blocking systems and wale shores. The sliding failure mode is modified to more accurately take into account the effects of cap angle.

A case study is undertaken involving the earthquake sliding failure of the USS *Leahy* (CG-16) while in a graving dock at Long Beach Naval Shipyard. This study verifies the accuracy and usefulness of the 3DOFRUB program. A parametric study is conducted to determine the effects of wale shores, isolators, and block stiffness and geometry variations on system survivability. The effects of using earthquake acceleration time histories with differing frequency spectrums on system survivability is studied.

Eleven submarine drydock blocking systems are studied using linear wood caps and bilinear wood caps for two different earthquakes, and 1-in. bilinear rubber caps. None of these systems survive to dry dock failure (0.26 g's) or even meet the U.S. Navy earthquake acceleration survivability criterion (0.20 g's). This shows that current drydock blocking systems are inadequate to survive expected earthquakes. Figure 32 illustrates the survivability levels of the various systems studied.

Two design solutions are found that meet the dry dock failure requirements. The low-stiffness solution uses dynamic isolators and rubber caps, and the high-stiffness solution uses wale shores and rubber caps. The survivability of these two solutions when excited by the 1940 El Centro earthquake is plotted in Fig. 33. This figure also includes the survivability of submarine system No. 1 using linear and bilinear wood, 1-in. rubber caps, and dynamic isolators. Both of the solutions have the same survivability level, and provide a reasonable margin of safety over the dry dock failure level.

Both of the design solutions survive beyond the dry dock failure level; however, each of the designs has its own advantages and disadvantages. Figure 34 is a comparison between the keelblock displacements for the wale shore solution and the isolator solution when excited by their respective design earthquakes. It is evident from this figure that the wale shore solution virtually prevents the submarine from moving horizontally relative to the dock floor. The isolator solution allows relatively large horizon-

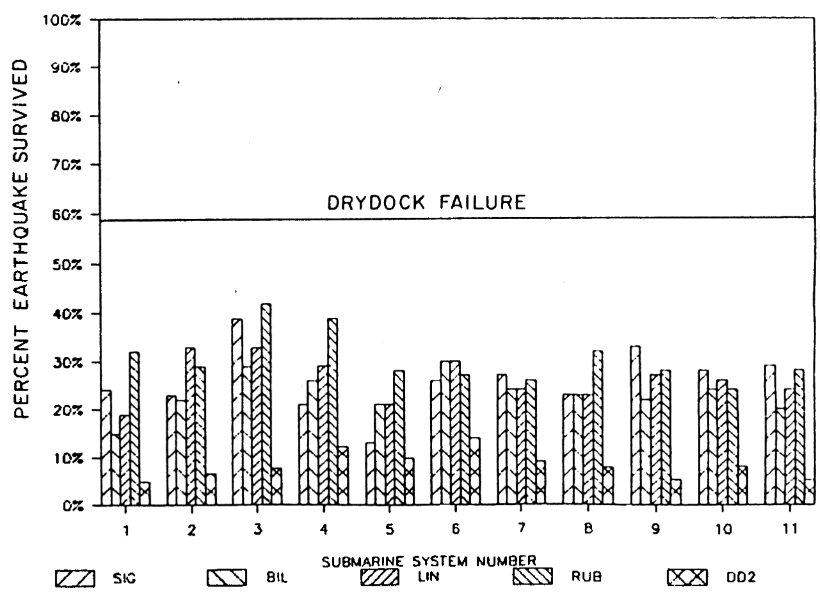

Fig. 32 Survival percentage comparisons: Sigman, bilinear, linear, and rubber (DD2)

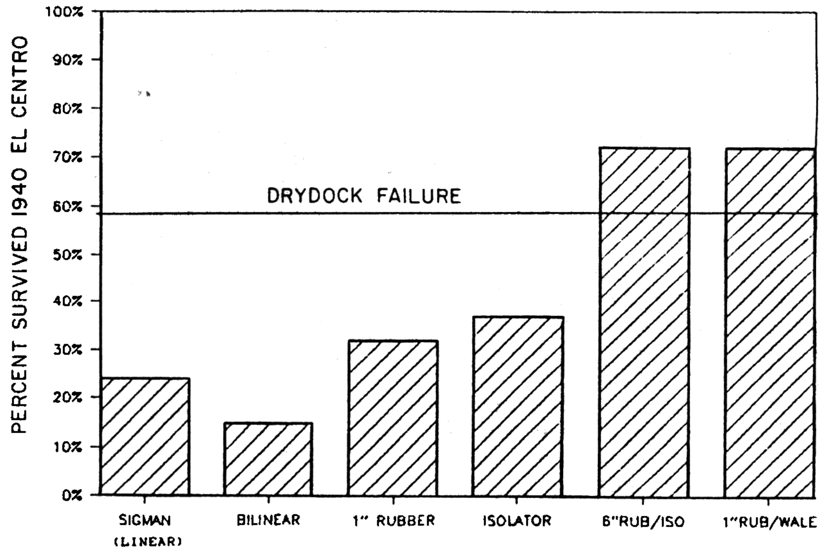

Fig. 33 Submarine drydock blocking system No. 1 survivability comparison

tal displacements to occur. Figure 35 is a comparison of the rotation of these two systems. Again, the wale shores are reducing movement.

The primary difference between the two design solutions is illustrated in Fig. 36. This figure is a comparison between the side block horizontal forces experienced by each solution. As seen in the figure, the wale shore system experiences forces which are an order of magnitude higher than those seen by the isolator solution.

The forces seen by the wale shore solution are also much more abrupt and higher in frequency. As expected, the wale shore solution follows the earthquake very closely. The wale shore high-stiffness solution almost rigidly attaches the submarine to the dry dock. Therefore, personnel and equipment inside the submarine will experience the full acceleration magnitudes of the earthquake.

The isolator solution nearly uncouples the submarine from the dry dock so that the submarine remains almost

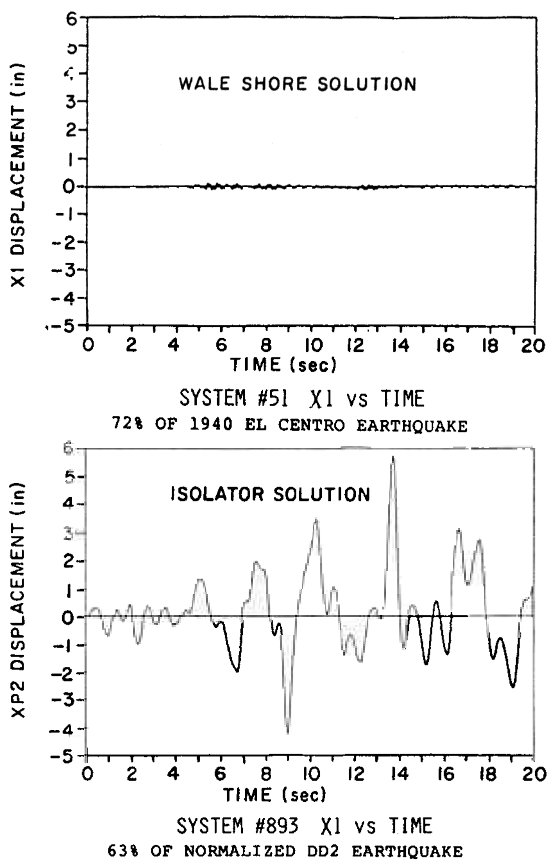

Fig. 34

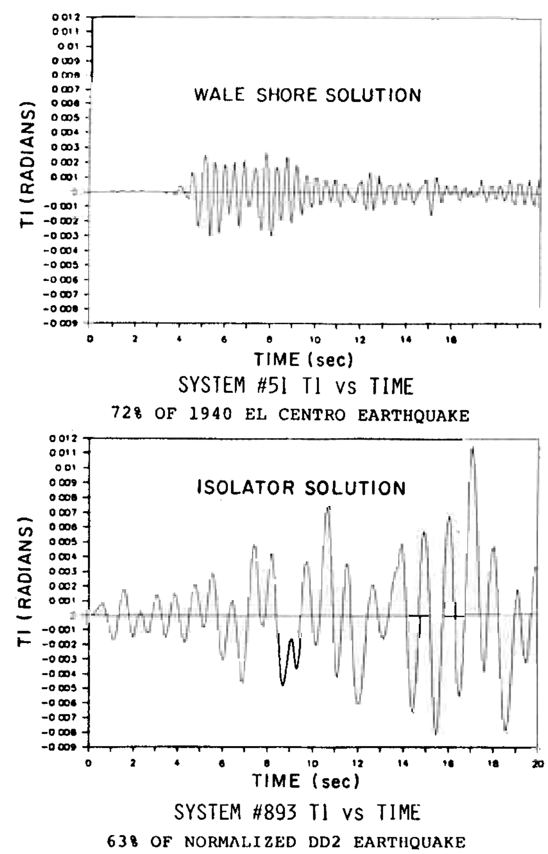

Fig. 35

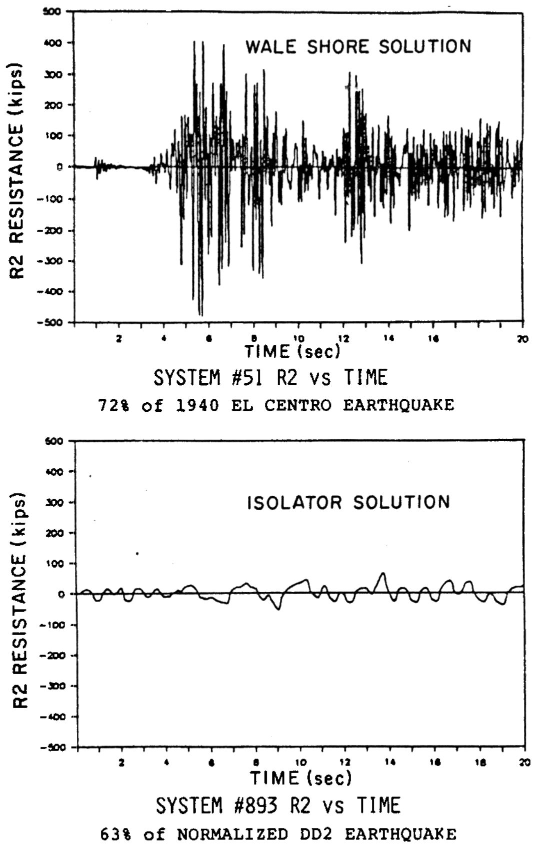

Fig. 36

fixed in space while the dry dock vibrates beneath. The accelerations experienced by the submarine are an order of magnitude lower than the earthquake accelerations. This substantially improves the safety of personnel and equipment inside the submarine. Even though submarines are designed to withstand large shock factors, when a submarine is in dry dock much of its equipment and machinery may be open for repairs. In addition, the shocks accompanying an earthquake may last well over one minute as opposed to the very short duration of an explosion shock wave.

Both of the design solutions can be constructed; however, there are some cost and interference concerns. The wale shore solution will interfere with access to the dry dock to some degree, although the wale shores could be used as utility runs and staging platforms. This solution's impact on the dry dock itself is nontrivial. The installation of 28 hinge assemblies along the dockside will be a major dry dock modification. In addition, the steel carriage and dry dock floor attachment fixtures are major changes to current drydocking practices and will require significant design and construction efforts.

Most of the modifications required to the blocking system and dry dock are within the capability of shipyards to accomplish. After a drydocking evolution has been completed, many additional man-hours will be required to install the wale shores. One wale shore per side can be removed for production reasons while still meeting the survivability criteria. The use of the steel carriage and rubber caps might reduce the hours required to lay out a blocking system. The measurements of the system would be locked into the construction, and it would be easier and faster to assemble this blocking system .with cranes. The use of rubber and steel in the blocking system would provide a much more reliable system than the present oak and Douglas fir.

The isolator solution may be the more expensive solution due to the large number and high cost of the dynamic isolators. However, this solution offers less production interference and a substantial increase in submarine personnel and equipment safety. The actual blocking system size increase will be limited to the cross-connections of the steel carriage, but significant changes will still be required to the dock floor to allow rigid attachment. Again, the use of the steel carriage and rubber caps should reduce the layout time of the drydock blocking system. Even though, using isolators, the submarine may move up to 6 in. horizontally during an earthquake, this motion is acceptable if appropriate precautions are taken in rigging services and platforms.

Considering the almost certain occurrence of a major earthquake in the proximity of a U.S. naval shipyard where submarines can be drydocked within the next 20 years, the expeditious incorporation of one of these design solutions into U.S. Navy drydocking standards is strongly recommended.

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Metric Conversion Factors

1 mile = 1.6 km
1 ft = 0.3048 m
1 in. = 2.54 cm
1 psi = 6.895 kPa