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# THE IMPACT RESISTANCE OF MODIFIED FERRO-CEMENT PANELS

by

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## ABSTRACT

The suitability of ferro-cement as a marine structural material is discussed and contrasted to other hull materials, particularly with regard to impact resistance. Established trends and findings regarding impact resistance of ferro-cement are reviewed. Mechanisms of impact failure are examined in general and in relation to materials used in this project.

Experiments are performed on several configurations involving ferro-cement with laminations of fiberglass reinforced plastic and sheet rubber, as well as unmodified ferro-cement. All configurations are chosen keeping in mind that most or all of the advantages of ferro-cement are to be retained.

The experiments show that vast improvements in impact resistance from a permeability viewpoint are possible, on an equal weight basis, over unmodified ferro-cement. Improvements of up to 500 per-cent are demonstrated.

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## I. INTRODUCTION

Ferro-cement has been found to be a desirable structural material for certain marine applications. Presently these applications are quite limited and reasons for this will be discussed below. It is appropriate at the outset however to set forth a definition of the material, particularly in view of its relatively recent usage as a boatbuilding medium.

### A. Definition

To those unfamiliar with the material, ferro-cement is often confused with reinforced concrete. Each material however does have its distinctive characteristics and it is appropriate to distinguish between them. Any definition should make this distinction and it should make it in terms of the contributing factors. Here the compelling factors are the inherent homogeneity of ferro-cement due to highly dispersed reinforcement and high strength mortar.

The Soviet Union (1) has adopted a tentative definition for ferro-cement and has stated representative design stresses based on the definition. This definition satisfies the above requirements and will be the one adopted here:

"True ferro-cement is considered to be a mesh reinforced mortar with a compressive strength of at least 400 kg/cm<sup>2</sup> (5700 psi) and a specific surface K (ratio

of surface area of steel wire to the volume of the composite) between  $2.0 \text{ cm}^{-1}$  ( $5.1 \text{ inch}^{-1}$ ) and  $3.0 \text{ cm}^{-1}$  ( $7.6 \text{ inch}^{-1}$ )."

For a specific surface greater than  $3.0 \text{ cm}^{-1}$  the material tends to lose compressive strength due to stratified layers of weakness associated with many superimposed layers of mesh and resultant poor penetration (2). For  $K$  less than  $2.0 \text{ cm}^{-1}$  but above  $0.5 \text{ cm}^{-1}$  the material is still assumed to be homogenous and isotropic for design purposes, but allowable design stresses are scaled in relation to  $K$  (1).  $K$  less than  $0.5 \text{ cm}^{-1}$  indicates reinforced concrete and design should proceed accordingly.

The middle portions of plate sections are commonly reinforced with steel rod primarily as an aid in the construction process. This portion is then excluded in calculating  $K$ .

#### B. Advantages and Disadvantages

It has been mentioned that ferro-cement has found only limited application as a marine structural material. The primary reasons for this are the material's strength properties when compared to the more familiar boatbuilding mediums of fiberglass reinforced plastic, wood, aluminum and steel. Indeed, a comparison of strength properties, normalized with respect to each material's density reveals the relative weakness of ferro-cement. Normalized tensile strength, compressive strength, Young's modulus, flexural

strength and shear strength of ferro-cement are all inferior to those of the other materials mentioned, in most cases dramatically so. (7)

It must follow then, that ferro-cement has certain overriding advantages to make it competitive for some applications. The most important of these are ease of fabrication and tooling costs. Construction is possible using unskilled labor for most of the process. Virtually no expensive equipment or molds are required; a major advantage over FRP. However, these comments must be modified for the case of volume production. To produce consistently high quality, economical hulls on a continuous basis, as much equipment is needed as for a plastic hull.

Material costs are generally lower in ferro-cement construction, but this is largely offset by increased labor requirements. Cost data are scarce in the literature, and it is difficult to generalize. Hagenbach (14), primarily in regards to small pleasure vessels, reported the total savings on completed boat costs to be 3-5 percent. Thus, while savings of 20 to 40 percent in hull materials are quite possible, it must be realized that this item represents a small portion of finished cost.

From the above considerations, it can be understood under what circumstances ferro-cement construction has flourished. In the case of do-it-yourself, one-off construction, labor cost is not a factor, and material savings

represent a larger portion of finished cost.

Ferro-cement becomes attractive in any situation where labor costs are low, construction facilities are minimal, low first cost is important, and high weight is acceptable. Its potential for developing nations is apparent and indeed the U. S. Navy and the United Nations are pursuing programs to introduce the material to such nations. A striking example was the successful use of 20 to 30 foot river patrol boats in the Vietnam conflict.

Ferro-cement has other attractive aspects. The combination of being completely inorganic and a fair thermal insulator makes this material one of the most fire resistant hull materials available and probably the safest from the point of view of danger to personnel from fire. Abrasion resistance is superior to wood and plastic. Maintenance requirements compare quite favorably since the material does not rot, corrode, and is impervious to worms. Indeed, since hydration normally continues for up to fifty years, strength increases with time. Appropriate coatings may be applied to counteract fouling or acidic materials. Adaptability to complex shapes is a definite advantage and has led to its use for wind tunnels, roofs, tanks, etc. It is easy to repair, but 14 to 30 days are required to reach full strength. Ferro-cement craft have been repaired at sea while making way.

The literature does not deal extensively with ferro-

cement in terms of its disadvantages. However, several conclusions are inescapable. First, as mentioned above, the strength to weight ratio is quite low. Applications are therefore limited to displacement vessels, work boats, barges, sailing vessels, etc. Lightweight , high performance craft are excluded.

Other drawbacks are associated with the newness of the material. Quality control of manufacture is a serious problem and is hampered by the lack of effective non-destructive testing techniques. Failure mechanisms are not well understood. Only in the last 5 years have a significant number of competent, technically trained investigators devoted their time to researching the material. Few systematic test results are available.

Lesser disadvantages include poor resistance to inorganic acids, difficulties in modifying existing structures, and inadequate information on joint design.

Several methods of hull fabrication are presently in common use, some suitable for one-off applications and others suitable for volume production. (2, 13) These will not be described here but are treated in detail in the rather vast popular literature on ferro-cement.

### C. Problem Statement

Impact resistance for ferro-cement can be characterized as being good or bad, depending on what viewpoint is taken and what materials are being compared. That is, a criteria

of failure must be agreed upon and there are several to choose from. On the plus side, it has been well established that the material under a shock load will sustain only very local damage. Catastrophic crack propagation does not occur; rather, local punch out occurs first. This is also characteristic of FRP and other composite materials. On the minus side, it will be seen below that the impermeability of the ferro-cement in the impacted area will be impaired to a much greater degree than in FRP at equal energy levels.

Resistance to impact damage is vital for any hull material. For small vessels, this property determines the scantlings in many areas of the hull. That is, local loading is usually greater than gross loads. The large majority of hull structural failures for small vessels result from some sort of impact, whether it be from striking a submerged object, colliding with another vessel, or moving against a piling while moored. It is virtually impossible to design against such unpredictable occurrences. However, if the hull or underwater portions thereof could be made more resistant to impact without a weight penalty, it would lead to a safer and/or lighter vessel.

A preliminary insight into the relative impact resistance of ferro-cement and FRP panels (from a permeability viewpoint) can be gained by comparing the work of Christenson (5) and Gibbs and Cox (10). Both materials were tested

with similar apparatus and procedures. Impact resistance is here defined to be the single strike impact energy required to produce the critical condition in the panel. The critical condition is considered to exist when water under a two foot head leaks through the damaged area at the rate of six gallons per hour. By extrapolating the Gibbs and Cox data to the point of equal weight, the FRP panels are found to be superior by an order of magnitude.

It is further enlightening to make a simple calculation with one of Christenson's data points. For a 1" thick ferro-cement specimen, which is a normal thickness for a 60' vessel, he obtained an impact resistance, defined above, of 400 ft-lbs. Making the gross assumption that the test set-up corresponds exactly to the full scale situation, the collision speed corresponding to critical damage can be calculated. That is, a 60' vessel weighing 50,000 lbs. could go no faster than 0.45 knots if it were to "survive" a head-on collision with a rigid deadhead having the same geometry as the test projectile. Obviously improvements in impact resistance are desirable.

#### D. Objective

The objective pursued in this study was to improve the impact resistance of ferro-cement from a permeability standpoint, to render it more suitable as a hull structural material and more competitive with other such materials.

This was done using not only configurations falling within the definition of ferro-cement but also selected "hybrid" or "doubly composite" configurations. The latter were selected keeping in mind that most or all of the advantages of ferro-cement should be retained.

## II. DISCUSSION

### A. Literature Survey

Almost all of the data on impact resistance to be found in the literature is qualitative in nature. Typically, crack widths and the dimensions of the deformed area are given with a description of projectile geometry and the incident energy. (5, 15) Since impact resistance is such a strong function of these parameters, comparisons are virtually impossible. In a few cases, impact damage is measured in terms of water leakage through the damaged area, certainly a relevant criteria for marine applications. However, comparisons are still difficult without standardized equipment and procedures.

In addition to actual damage measurements, several trends have been established. Key (15) has demonstrated definite relationships between impact performance and tensile strength of continuous reinforcement. Deformations and leakages vary inversely with the reinforcement tensile strength. For fibrous reinforcement, he concluded that the fibers had no effect on the dynamic cracking strength but served only to hold the fracture surfaces together after cracking. Fibrous reinforcement, being randomly oriented, should have more steel placed in a more beneficial direction to resist tensile fracture than would layered reinforcement. It was logically concluded then that

layered reinforcement should have no effect on dynamic strength of the mortar. The role of the reinforcement as only holding the fractured mortar together is apparent. Key's work also indicated fibrous reinforcement to be inferior to continuous in terms of deformations except for extremely high aspect ratios.

The mechanical holding action is of course vital when considering watertightness. Bezukladov (1) noted that a crack width of less than .001 mm will not seep water. Above this width, water flow will increase as a function of the area of the opening and the head. To take advantage of the action of the reinforcement in reducing crack widths and therefore flow, it would seem reasonable to use small size mesh for the outer layers of reinforcement. Key has confirmed this. There is of course a trade-off between mesh size and ease of penetration of mortar.

Several investigators (1) (15) (20) (29) have confirmed that tensile and impact performance of ferro-cement are intimately related to the specific surface of reinforcement, defined earlier. Indeed it is this property which is primarily responsible for the distinction between ferro-cement and reinforced concrete. Bezukladov (1) found that as the specific surface increases, crack resistance increases, but ultimate tensile strength is dependent on the total reinforcement. Naaman (20) also observed that the breaking load of samples in tension depends only upon the total

amount of reinforcement present. He also noted that cracking resistance of the composite increases linearly with specific surface. However, little energy is required to produce cracks which would allow sea water access to the reinforcement. Naaman also observed an increase in ultimate strain with specific surface for the same ultimate load. Finally, other conditions being equal, the mechanical properties of the reinforcement (apparent modulus of elasticity, yield and ultimate stress, ductility) are to some extent reproduced in the composite properties. High strength brittle steel results in high ultimate stress, low energy absorption and sudden failure for the composite. Low strength ductile steel results in low ultimate stress, high energy absorption and visible cracking.

The type of impact failure most usually reported in the literature involves the fracture of the mortar on the back face as a result of reflected tensile waves. This failure involves spalling of the inside surface and if there is poor cross connection between mesh layers, internal delamination can also occur.

Bezukladov (1) reports a second type of failure which, if sufficient energy is available, will cause punch out. The resistance of ferro-cement to this type of failure would depend on its resistance to transverse shear. It is obvious that such failure would occur at energy levels above those necessary to destroy functional watertightness.

Several mathematical models have been proposed for designing in ferro-cement (12) (17) (18). Considering the number of variables involved in present day usage of the material, these models are necessarily quite limited in scope, and are based on a certain set of data. Certainly a limited testing program would be in order before applying any such model. None of the models attempts to predict impact resistance.

A limited amount of data is included (Figures 1, 2, 3 and Tables 1, 2) to provide a quantitative insight into impact resistance of ferro-cement. It is reiterated that data similar to that of Table 2 is abundant but of limited value. Comparisons are impossible with other experiments using different panel sizes, projectile geometries, means of support etc. Figure 1 from Shah (29) is included to illustrate the effect of specific surface and ductility of reinforcement.

Figures 2 and 3, from (10) and (5) respectively, provide a graphic comparison between FRP and ferro-cement panels. These plots show the single strike impact energy necessary to critically damage a panel (6 gal/hr leakage) of a given thickness. The FRP panels have a specific gravity of about 1.67 and the ferro-cement about 2.72. When normalized with respect to weight, the FRP is better by an order of magnitude. These tests were conducted using completely similar equipment and specimen geometries so the comparison is thought to be valid.

The following is a very brief summary of significant findings regarding impact and related strengths for ferro-cement:

1. Impact resistance from a deformation or leakage viewpoint increases with specific surface, strength of reinforcement, mortar tensile strength and mortar shear strength.
2. Dynamic cracking strength increases with specific surface and is not affected by strength of reinforcement.
3. The reinforcement acts as a crack arrestor and localizes the damage to the point where local punch-out occurs before crack propagation.
4. Ultimate tensile strength is equal to that of the reinforcement.
5. Ultimate strain increases with specific surface.
6. Toughness of the reinforcement is reflected in that of the composite.

It must be borne in mind that to date no real breakthroughs have been made in improving impact resistance by optimizing the make-up of the material itself. That is, improvements possible with the basic material do not approach an order of magnitude.

#### B. Theory

When a material is stressed with a suddenly applied load the deformations and stresses are not immediately transmitted to all parts of the body, remote portions of the body remaining undisturbed for some time. Deformations and stresses progress through the material in the form of one or more transient disturbances (waves) which travel at a finite velocity from the area of application of the load. Such a suddenly applied or impulsive load may be produced by a sharp mechanical blow, a detonating explosive or by impact of

a high velocity projectile. Regardless of the method of application the consequent stress disturbances have identical properties.

Any elastic wave will be reflected when it reaches a free surface of the material in which it is travelling. The simplest case occurs when the wave strikes the free surface normally. In a longitudinal wave, since the stress normal to the surface at the surface must be zero, the reflected pulse must be opposite in sense to the incident pulse (compression reflected as tension and vice versa).

In the case of a sphere impinging on a plate, a compressive wave is generated at the point of contact and propagates spherically outward. It approaches the free surface at the opposite side of the plate and is reflected at normal incidence. The reflected wave is tensile, and interferes with the remainder of the still propagating compressive wave. The resulting wave is then the algebraic sum of the waves, and is first decreasingly compressive and then increasingly tensile. When the resulting tensile wave builds to a sufficiently high level to exceed the dynamic cracking strength of the material, a fracture occurs beneath the free surface. In unreinforced concrete this fracture would result in a spall. Succeeding reflections of sufficient strength would result in additional spalls. For ferro-cement the spalling is greatly reduced by the action of the reinforcement. Indeed, for moderate energies only internal damage will result, not visible from the free surface.

In a composite material, interfaces as well as free surfaces are present. A pulse will be modified as it crosses this boundary. In general the pulse will be partially transmitted and reflected.

The laws which govern the modification of the pulse as it crosses the interface are derived from the two boundary conditions. First, the stresses on the two sides of the boundary are equal and second, particle velocities normal to the boundary are equal. The equations which express the above conditions can be written as

$$\sigma_I + \sigma_R = \sigma_T \quad (a)$$

and

$$V_I + V_R = V_T \quad (b)$$

where  $\sigma_I$ ,  $\sigma_R$ ,  $\sigma_T$ ,  $V_I$ ,  $V_R$  and  $V_T$  are the instantaneous values of stress and particle velocities, respectively, for the incident, reflected and transmitted waves, respectively.

The relationship between stress and particle velocity,  $\sigma$  and  $V$ , at any point comes from Newton's second law

$$Ft = mV \quad (c)$$

where  $F$  is the force acting on a given cross section,  $t$  is the time the force acts,  $m$  is the mass it acts against, and  $V$  is the velocity imparted to  $m$  by  $F$ . Stated in differential form this becomes

$$Fdt = d(mV). \quad (d)$$

For a body of unit crosssectional area  $A$ ,

$$\sigma = F/A = F \quad (e)$$

and

$$dm = \rho d(\text{volume}) \quad (f)$$

where  $\rho$  is mass density. But for unit cross section,

$$d(\text{volume}) = Ads = ds \quad (g)$$

where  $s$  is distance along the wave. Therefore,

$$dm = \rho ds. \quad (h)$$

Combining equations (d), (e) and (h) one obtains

$$\sigma dt = \rho dsV \quad (i)$$

or

$$\sigma = \rho \frac{ds}{dt} V. \quad (j)$$

But

$$c = \frac{ds}{dt} \quad (k)$$

where  $c$  is wave velocity so that

$$\sigma = \rho cV \quad (l)$$

and

$$V = \sigma/\rho c. \quad (m)$$

In equation (b) then it follows

$$\begin{aligned} V_I &= \sigma_I/\rho_1 c_1 \\ V_R &= -\sigma_R/\rho_1 c_1 \\ V_T &= \sigma_T/\rho_2 c_2 \end{aligned} \quad (n)$$

where subscripts denote the first and second mediums. Substituting equations (n) into (b),

$$\frac{\sigma_I}{\rho_1 c_1} - \frac{\sigma_R}{\rho_1 c_1} = \frac{\sigma_T}{\rho_2 c_2} \quad (o)$$

and solving (a) and (o) simultaneously, first for  $\sigma_T$  in terms of  $\sigma_I$ , then for  $\sigma_R$  in terms of  $\sigma_I$ , the two fundamental equations governing the distribution of stress at an abrupt change in media will be obtained:

$$\sigma_T = \frac{2\rho_2 c_2}{\rho_2 c_2 + \rho_1 c_1} \sigma_I \quad (p)$$

$$\sigma_R = \frac{\rho_2 c_2 - \rho_1 c_1}{\rho_2 c_2 + \rho_1 c_1} \sigma_I \quad (q)$$

These equations have several inherent implications which are valuable aids in understanding why and how the pulse is modified at an interface. By dividing (p) by (q) the ratio of stress transmitted to stress reflected is obtained:

$$\frac{\sigma_T}{\sigma_R} = \frac{2\rho_2 c_2}{\rho_2 c_2 - \rho_1 c_1} \quad (r)$$

Thus when  $\rho_2 c_2$  is approximately equal to  $\rho_1 c_1$  nearly all the stress is transmitted, whereas if  $\rho_2 c_2$  differs greatly from  $\rho_1 c_1$  most of the stress is reflected.

The material parameter  $\rho c$ , called specific acoustic resistance is seen to be basic to the nature of propagation of waves. it depends only on the elastic constants and density of the material,

$$\rho c = \left( \frac{\rho E(1-\gamma)}{(1+\gamma)(1-2\gamma)} \right)^{1/2}$$

where  $\gamma$  is Poisson's ration. Thus  $\rho c$  is seen to be a measure of rigidity.

Other implications of equations (p) and (q) are as follows. In (p) the coefficient of  $\sigma_I$  can never be negative; thus tension is transmitted as tension and compression as compression. Also, a striking feature is illustrated when  $\rho_2 c_2 \gg \rho_1 c_1$ , that is, medium two is much more rigid than medium one. In this case the stress of the transmitted pulse is approximately twice the stress of the incident wave.

In equation (q) the coefficient of  $\sigma_I$  can be positive or negative depending on whether  $\rho_1 c_1 \ll \rho_2 c_2$  or  $\rho_1 c_1 \gg \rho_2 c_2$ . If negative, incident compression stress is reflected as tension

stress and vice versa. If positive, incident compression is reflected as compression.

In a laminated material, the nature of the interface itself is important. In particular the effect of a gap at the interface will be of interest here. A gap exists when the space between laminations is not occupied by a bonding agent. The resulting space will probably be filled by air which is acoustically comparable to a vacuum (very low  $\rho c$ ).

The most obvious characteristic of a gap is that stress cannot be transmitted across it if it has a finite width. If the width is reduced to zero, only compressive stress can be transmitted. When any pulse reflects from the free surface of a material, the free surface is set into motion. If the pulse strikes normally, the surface velocity is  $2V$  where  $V$  is the average particle velocity of the amount of the pulse reflected. It is obvious that if the surface maintains this velocity for any finite time it will move a finite distance. If the gap is small enough, the distance the surface moves will be sufficient to close the gap and allow transmission of a compressive stress. Thus only a part of the incident wave can be transmitted across the gap. Before the gap was closed, the wave was wholly reflected.

For laminations with no intervening bond then, the incident pulse is seen to transmit into the second material and there remain "trapped" since the reflected wave will be tensile at the interface. This would hold for the first and largest reflected wave. Thereafter interactions between subsequent smaller reflections would introduce some compressive pulses at the interface.

For a homogeneous material, several other aspects of the effects of impact could be theoretically predicted. These include wave shapes, particle velocities, spall size and number of spalls. None of these are of particular interest here. The primary objective here is to determine and improve impact damage as manifested by leakage rates, and this cannot be predicted analytically. Certainly, however, it is hoped to explain and understand any findings in terms of what has been discussed here.

As will be seen in the testing section there are four materials of prime interest in this investigation. These are concrete, steel, glass reinforced plastic and neoprene foam rubber. To characterize the behavior of combinations of these materials under impact loading their specific acoustic resistances must be known.

The following tabulation then lists assumed and calculated values used in calculating specific acoustic resistances with equation (s).

	Specific Gravity	Young's Modulus psi	Poisson's Ratio	Specific Acoustic Resistance lb-sec/ft <sup>3</sup>
Concrete	2.32	$2 \times 10^6$	.12	36,600
Steel	7.85	$30 \times 10^6$	.31	301,800
FRP	1.67	$1 \times 10^6$	.35	27,300

A value was not calculated for rubber but certainly it is several orders of magnitude below those listed because of its low modulus. It is seen that concrete and FRP have comparable values and steel has the highest value by an order of magnitude.

For ferro-cement, where steel reinforcement is encased by concrete, we have the case where  $\rho_2 c_2 \gg \rho_1 c_1$ . The foregoing

considerations then suggest that incident compressive stress waves will be reflected as compressive waves. Moreover, due to the high dispersion of the reinforcement there will be many such reflections interacting with each other and those from free surfaces. It remains to be seen whether these effects will or will not allow the neglect of the effect of reinforcement on the performance of the composite.

Consider now a lamination of ferro-cement and rubber sheeting. The rubber should remain largely unaffected by an incident compressive wave because of its low specific acoustic resistance; the theory predicts that little stress will be transmitted to the rubber.

A lamination involving FRP should not affect stress waves at the interface due to the comparable specific acoustic resistances. This would not hold of course if the bond became impaired and gap effects were operating.

### III. EXPERIMENTS

#### A. General

The stated objective herein is to improve the impact resistance of ferro-cement. Configurations to be tested do not all fall within the definition of ferro-cement. However, if a certain configuration maintains most or all of the advantages of ease of fabrication, cost, low maintenance, etc. and shows improved impact resistance, it will be considered to be an "improvement." What one wishes to call the result is academic. Here it is referred to simply as modified ferro-cement.

Homogeneous materials are often tested for impact strength by an Izod test in which a small notched or unnotched sample about 1/2 inch square is clamped as a vertical cantilever beam and struck by a swinging pendulum. The test is run on a series of samples under standard conditions and the energy necessary to break the sample is determined.

The Izod test is less applicable to composite materials. It gives the energy absorbed at failure and not at partial failure as usually occurs in composite materials and certainly as occurs in ferro-cement. An alternative procedure is called for.

Since this investigation is directed primarily at marine applications, the criteria used in (5) and (10),

mentioned earlier, are particularly relevant; that is, to measure impact damage by leakage rates and relate this damage to the absorbed energy. Such a procedure is used here. This is also in accordance with the recommendation of Bezukladov (1), which was to measure energy at failure as  $\sum_{n=1}^m P_n H_n$  or simply the sum of weights times heights of fall. Of special interest is the case where  $m=1$  (single strike impact) and where the specimen has reached its defined condition of failure. A method for predicting this single strike energy is described under Test Procedures.

Configurations tested include laminations of ferro-cement and FRP or rummer. The basic motivation for this was that impact resistance of the basic material cannot be greatly improved by optimizing the primary constituents of steel mesh, steel bar, cement, sand and water. It seems intuitively probable that greater improvements could be made using combinations of these high impact strength materials. And this intuitive conclusion is reinforced by considering the mechanisms of impact failure discussed under Theory.

Every effort has been made to allow comparison of the results of the present experiments with others in the literature. Other testing programs have used impactors ranging from 1/2" diameter balls to 10" diameter oxygen tanks filled with lead shot. Types of support range from

small panels suspended as pendulums to full scale tests with a completed hull. Failure has usually been judged on a semi or fully qualitative basis.

In particular, the present experiments use similar apparatus and procedures to those of Christenson (5) and Gibbs and Cox (10). The failure criterion and measurement of applied load have been described earlier. It is felt that this procedure yields the most useful and relevant information as far as marine applications are concerned.

#### B. Specimens

A total of ten sets of specimens, each 18" square were fabricated for testing. Specimens in any given set are identical. Set I consists of four specimens and sets II through X consist of two specimens each. Since the primary goal was to measure the effectiveness of several different laminations, the ferro-cement itself was made up to conform as nearly as possible to current practice.

A detailed tabulation of the configuration and characteristics of each set of specimens is given in Tables 3 and 4. The reinforcement used throughout was galvanized welded (unwoven) steel mesh and .243" diameter steel rod. The mesh was 19 gauge wire (.041" diameter) with 1/2" openings. Wire ultimate strength was determined to be 89 ksi. The rod was high carbon spring steel with ultimate strength between 190 and 210 ksi.

The nature of welded mesh allows it to be layered in several ways. If two layers are nested then the top wires of the bottom layer and the bottom wires of the top layer are running the same direction and are at the same level. Thus, two layers of mesh occupy three wire diameters in thickness, and minimum thickness is achieved. If two layers are not nested, maximum thickness is achieved. In this case the layers may be staggered or unstaggered in one or both directions. Nesting necessarily implies staggering in at least one direction. The reinforcement for the panels in Table 3 was staggered in both directions.

Since high weight is one of the principal penalties involved in ferro-cement construction, the weight of all specimens was held constant. It is felt that this allows the most direct and useful comparisons to be made. Thus in panels involving a lamination, the thickness of the ferro cement was reduced to bring the total weight to the constant value. Excepting Panels II, which were not tested, the mean of panel weights was 33.11 lbs., with a minimum of 31.31 lbs. and a maximum of 34.09 lbs. Weights of individual panels are found in Appendix A and Table 4.

The basic thickness for unmodified ferro-cement panels was chosen to be 1" which corresponds typically to a 50 to 75 foot vessel; laminated thicknesses varied.

Type III Portland cement (high early strength) was used which is not normal practice but necessary here in

the interests of time. The aggregate was fine silica (Ottawa) sand with a fineness modulus of 2.45. A sieve analysis is found in Appendix B.

Water to cement ratio and sand to cement ratio were 0.45 and 1.5 (wt.) respectively. The former was found to be the minimum for adequate ease of penetration of the mortar into the mesh. Also, the sieve analysis shows that particles larger than 1/8" were removed, also to promote penetration. The water to cement ratio is based on the sand being in the saturated surface dry condition. Chromium trioxide was added to the mix water in the amount of 300 ppm (wt.) in accordance with Williamson's recommendation (32). It acts to inhibit any galvanic action between the uncoated rods and galvanized mesh during curing. Relevant densities in lbs. per cubic foot were: cement, 94; sand, 105; concrete, 146; and ferro-cement (sets I and X), 172.

Wood molds, Figure 4, were used to lay up the specimens. Filler pieces were inserted in the bottom of the molds to provide the desired thickness. Slots in the sides of the molds on 2" centers provided positive placement of the rods, which then protruded 1/2" from the finished panels. Extra strips of 1" wide mesh were placed in the bottom of the molds to provide about 0.1" concrete cover over the reinforcement. Similar cover was provided at the top of the specimens. Mesh and rods were wired tightly together

and were also anchored to the bottom of the mold. A coating of oil or a sheet of Mylar plastic provided easy mold release.

Mixing was done with a modified commercial food mixer, found to be suitable for the low water content (Figure 5). Each batch was mixed for 6 minutes. After 5 minutes, the sides of the bowl were scraped down. Three 2" cubes for compression testing were made for each batch in accordance with ASTM C-109. Two specimens could be made from each batch. The mortar was placed with trowels and the molds were vibrated for two minutes during placement. Longer vibration periods produced excessive surface water.

Curing was done in a moist room, 100% relative humidity and 72° for seven days. Molds were stripped after 24 hours. Testing (compressive and impact) was performed two days after removal from the moist room or nine days after mixing. This allowed time to laminate the panels as desired.

FRP laminations were laid up by hand immediately after removal from the moist room. Curing took place at room temperature for two days. The matrix acted as the bonding agent.

It will be seen that no data is presented for sets II, V and VIII. In the first, penetration of the mesh into the mortar was quite poor and the panels were not tested. Rather, the lay-up was changed slightly (Panels III)

to promote penetration. For Panels V and VIII the FRP lamination on the side opposite the impactor separated from the ferro-cement early in the testing and further testing was not possible.

### C. Apparatus

Equipment used for impact testing was self-devised but modeled after that used in (5) and (10) to allow comparisons of results. See Figures 6, 7, 8, 9, 10 and 11.

The projectile was a 3" chromium steel ball (annealed) threaded to a 5' long 5/8" diameter steel bar for attaching weights. The weights were 4" OD x 11/16" ID steel cylinders which slid over the 5/8" rod. The projectile with no weight weighed 9.44 lbs. Total projectile weight could be varied from this value to 205 lbs. in approximately 1 lb. intervals. The projectile was suspended from an overhead I beam and was raised using a block and tackle.

The support stand provided simple support on four sides for the specimen, and was made from 1 - 5/8x 3/8 flat bar. Inside dimensions were 16" x 16".

Leakage tests were done using a wooden water box with a foam rubber gasket attached to the specimen by C-clamps. Applied head was 2 feet. Inside dimensions were 12" x 12".

### D. Test Procedure

Each specimen was subjected to one of the following

series of impacts:

Series 1: 25, 50, 75, 100....ft. lbs.

Series 2: 50, 100, 150, 200....ft. lbs.

Series 3: 100, 200, 300, 400....ft. lbs.

The energy of each strike is the height of drop multiplied by the weight of the projectile. With one exception, energies were varied by changing projectile weight, keeping height virtually constant. Heights varied between 4.59 and 4.74 feet. Impact velocity was then about 12.25 fps or 7.25 knots which is of the same order as the speed of any displacement vessel. For the 25 ft. lb. impact, the minimum projectile weight required a lower drop height of about 2.65 ft.

At the outset it was desired to determine the critical single strike impact energy required to place the panel in the defined condition of failure (6 gallons per hour leakage). To do this required that 4 specimens of each configuration be fabricated and tested. Each of the first three would be subjected to one of the above impact series. Then by a process of cross plotting the resulting curves of leakage versus cumulative energy, the critical single impact could be predicted and applied to the fourth specimen. For two reasons, this was done only for specimen set I. The main reason was the prohibitive time involved in fabricating and testing four specimens. The second reason will be discussed under Results.

Sets III through X were then tested using only impact series 1 and 2. Definition of load at failure was then changed from the critical single strike energy to the integrated area of the curves of leakage vs. energy. In particular, as will be seen, the impact resistance of any given configuration, or specimen set, was taken to be the average of areas under the two curves of leakage vs. energy up to a leakage of 6 gallons per hour, where one curve corresponds to impact series 1 and the other curve corresponds to impact series 2.

Series 3 then was used only on specimen I-D. Specimen I-B was subjected to the predicted critical single strike energy. Results will be discussed below.

After each strike the dimensions of the damaged area were measured and recorded. If indicated, the water box was filled and leakage measured. The water box remained attached during impact.

Leakage was measured for the first 15 minutes after water was introduced into the box, and the result multiplied by four to obtain the hourly rate. This was done because the leakage has been found to decrease with time; as much as 80 percent in several hours (5). The initial leakage is the highest and of the most interest. Obviously the loosened particles (spalls) are reoriented by the flow and reduce the leakage. It should be mentioned that about 90 seconds was required to fill the water box. Test data are found in Appendix A.

#### IV. RESULTS

Curves of leakage vs. cumulative energy are plotted in Figure 12. Intergrated areas and averages thereof are presented in Table 5, as is the mortar compressive strength.

Plots and cross plots pertaining to specimen set I are given in Figures 13 and 14. It is seen that the predicted critical single strike impact was 175 ft. lb. When this energy was applied to the fourth panel in the series, a leakage of 0.05 gal/hr. resulted.

For reasons already mentioned, no results are given for panels II, V, VIII. Since panels VII shattered with one strike the impact resistance was zero. Typical impact damage is illustrated in Figures 15 through 17.

The results for Panels I point out the second reason for not pursuing this method of testing. Three panels are apparently not sufficient to make an accurate prediction of the critical single impact. To sue this method would require defining failure to be any leakage between certain relatively wide limits. And if this is done, it may well be easier to determine the same result by trial and error.

Undoubtedly the determination of single strike impact resistance is desirable in terms of being more meaningful to the designer. It is thought however that results obtained here are of no less value for comparing different configurations. And as mentioned earlier, design against impact is at best qualitative in nature.

It should be noted that Panels X are identical to Panels I. They were made up and tested only because of procedural errors made with Panels I. It is these panels which are considered to be typical of current practice and are the base to which other configurations are compared.

A glance at the results of this investigation shows the combinations of FRP and ferro-cement with the FRP on the impacted side to be superior to the other configurations tested. A 500% improvement over un laminated ferro-cement is realized. However, it must be borne in mind that only one of eight of the FRP laminations tested remained bonded to the ferro-cement up to the failure condition; certainly this is an unacceptable situation. The FRP could be mechanically attached to the base material, but this introduces a host of difficulties.

It might be asked why the FRP laminations were bonded using only the matrix as the adhesive. It is likely that a resilient low modulus adhesive such as a mastic or rubber would well withstand the shock loading. The answer of course lies in the consideration of the full scale application. Any lamination must necessarily be laid up directly on the hull. It cannot be prefabricated and applied later due to the compound curvature involved. No adhesives are available which could be successfully used with the liquid resin and still perform their function.

The impetus for testing epoxy matrices in Panels VIII

and IX was the early and complete debonding of the polyester matrices of Panels IV and V. The epoxies are remarkable adhesives to be sure but still were not successful here. It is noted that it was the epoxy matrix of Panel IX-A which was the only one to remain bonded out of the 4 polyester and 4 epoxy samples tested. Further work would be in order with other epoxies and/or surface treatments to improve the bond.

A lesser drawback of the FRP matrices was the labor and time involved in fabrication. It is estimated that approximately half as much time was spent making the lamination as the base material.

These considerations lead to the conclusion that the rubber lamination of Panels VI was the most successful configuration in this investigation. The rubber used was a neoprene foam primarily because of its low cost. Much stronger solid rubbers are available. Nonetheless a 270% improvement was realized over the basic ferro-cement (Panels X). Debonding did not occur except immediately below the impacted area. When failure did occur it was sudden and was promoted by the cutting action of loosened concrete particles (spalls) and fractured reinforcement, providing notches and stress concentration under the hydrostatic head.

Labor involved in laminating the rubber was minimal, using only common neoprene bonding cement. It is felt that use of a higher quality rubber or a fiber reinforced

rubber would prove superior to FRP from viewpoints of actual impact resistance, cost and labor.

Figure 12 shows that, for a given configuration, areas under the leakage curves are approximately the same for impact series 1 and 2. The exceptions are Panels IX. Here the difference is attributed to the debonding of the lamination in IX-B whereas IX-A did not debond. The theory provides an explanation. It is remembered that the cement and FRP have nearly equal specific acoustic resistance. Thus for the intact panel the incident compression is transmitted virtually without change across the interface into the concrete. Upon reflection from the free surface, energy is expended creating fractures and spalls. The reflected stress when reentering the FRP is then greatly reduced in magnitude and does little damage. In the debonded panel a part of the incident compression is reflected at the intervening interface before the gap is closed. This reflection is much less diminished than in the previous case and thus much more able to impair the FRP.

It is unfortunate that testing could not be completed on Panels V and VIII (FRP lamination opposite projectile). However, the theory would predict that they would be inferior to panels laminated on the impact side. Assuming a bond could be maintained and realizing it is the FRP which is providing virtually all of the impact resistance, it is desirable to expend most of the impact energy in

disrupting the cement, which becomes somewhat useless very soon anyway. This is accomplished by allowing the reflected tension to "work" first upon the cement.

Few conclusions can be drawn from this work regarding interactions of reflected stresses from the steel reinforcement. The composite appears to behave as though the steel were absent except of course for the crack arresting actions. That is, cleavage failures occur only on the far side as expected. Obviously no significant reflected tensile stresses are acting elsewhere.

Panels III were tested to ascertain the effect of highly dispersed reinforcement throughout the specimen. Specific surface and steel content were nearly the same as for Panels X. Impact resistance was not changed.

Performance of the rubber laminate was in agreement with the theory, which predicted it would be virtually unaffected by incident stress pulses. Indeed the rubber did not fail under impact at all but rather under tensile membrane stresses due to the head of water in the leakage test.

Panels VII were tested only to find out how "bad" unreinforced concrete would be. Since both panels were shattered by the smallest impact used in this work, the role of the reinforcement was very graphically illustrated.

## V. CONCLUSIONS

On the basis of this study the following conclusions are drawn:

1. The impact resistance of ferro-cement, from a permeability standpoint, can be vastly improved by providing a lamination with good impact properties, whether these properties derive from a low modulus of elasticity or high tensile strength.
2. Such improvement is possible while still maintaining the advantages of ease of fabrication, low cost, low maintenance and many of the lesser advantages of ferro-cement.
3. Rubber laminations appear to be more feasible than fiberglass reinforced plastics.
4. Criteria and procedures used herein are found to comprise an efficient and useful method to measure the impact resistance of conventional or modified ferro-cement.

## VI. RECOMMENDATIONS

Further testing would be desirable with configurations not tested here. Higher strength solid rubber or possibly nylon fabric appear promising as laminations.

Also, work is needed to improve bond strengths between FRP and cement to render this combination more feasible for hull structures.

## ACKNOWLEDGEMENTS

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TABLE 1

Panel Construction Details

For Table 2  
From (12)

<u>Panel Number</u>	<u>Description</u>
44	Rods--high tensile double-drawn rods, 0.225 inch diameter, spaced at 2 inch centers in each direction.  Mesh--1/2"-19 gauge hardware cloth, 3 layers on tension side, 2 layers on the other side.
45	Rods--same as panel 44.  Mesh--1/2"-16 gauge hardware cloth, 1 layer on each side of rods.
46	Rods--same as panel 44.  Mesh--1/2"-22 gauge hexagonal mesh, 5 layers on each side of rods.
48	Rods--none (rods were initially set at 6 inch centers but were pulled from panel after initial set).  Mesh--same as panel 44.
55	Rods--high tensile double drawn rods, 0.225 inch diameter, spaced at 4 inch centers in each direction.  Mesh--same as panel 44.

TABLE 2

Results of Drop-Impact Load Tests on 36 inch Panels

See also Table 1  
From (12)

Panel No.	Dishing in 1/16 in.	Diameter of circle encom- passing cracks in.	Rectilin- ear crack extension from center in.	Description of Bottom Surface
44	4	12	17	Very fine radial cracks. One fine rectilinear crack.
45	8	15 x 18	6	Fine radial cracks. Fine rectilinear cracks.
46	9	30	0	Radial cracking.
48	18	32	18	Fine radial cracking. One rectilinear crack open 1/16".
55	10	24	17	Radial cracking. Fine rectilinear crack. Center spalling over 6" diameter.

TABLE 3

Configurations of Panels

Note: Each entry describes the layup from the bottom to the top (impacted) side. The top side is also the same as the trowelled side.

Panels I: Ferro-cement; 3 meshes (nested), rods on 2" centers both directions, 3 meshes (nested). No lamination.

Panels II: Ferro-cement; 3 meshes (nested), 6 meshes (unnested, staggered), 3 meshes (nested). No lamination.

Panels III: Ferro-cement; 3 meshes (nested), 6 meshes (unnested, every 2 staggered), 3 meshes (nested). No lamination.

Panels IV: Ferro-cement; 3 meshes (nested), 1 mesh (unnested, staggered), rods on 2" centers in one direction, 3 meshes (nested). Lamination; 1 random mat, 6 woven roving, 1 random mat in polyester matrix.

Panels V: Lamination; same as in Panels IV. Ferro-cement; same as in Panels IV.

Panels VI: Lamination; 3/16" thick neoprene foam rubber, neoprene bonding cement (Atlantic brand). Ferro-cement; 3 meshes (nested), rods on 2" centers both directions, 3 meshes (nested).

Panels VII: Unreinforced concrete. No lamination.

Panels VIII: Same as Panels V except that lamination uses epoxy matrix.

Panels IX: Same as Panels IV except that lamination uses epoxy matrix.

Panels X: Same as Panels I.

TABLE 4

Non-Performance Characteristics of Specimens

	Thickness inches		Weight lbs		Specific Surface F-C only in <sup>-1</sup>	Steel Content F-C only lb/ft <sup>3</sup>
	F-C	Total	F-C	Total		
Panels I						
A	1	1	NM*	NM	6.18	44.69
B	1	1	NM	NM	6.18	44.69
C	1	1	NM	NM	6.18	44.69
D	1	1	NM	NM	6.18	44.69
Panels II						
A	1	1	28.50	28.50	6.18	41.15
B	1	1	28.31	28.31	6.18	41.15
Panels III						
A	1	1	32.38	32.38	6.18	41.15
B	1	1	31.31	31.31	6.18	41.15
Panels IV						
A	7/8	1 1/16	28.88	33.48	5.77	41.20
B	7/8	1 1/16	28.12	32.61	5.77	41.20
Panels V						
A	7/8	1 1/16	29.20	33.75	5.77	41.20
B	7/8	1 1/16	29.45	34.06	5.77	41.20
Panels VI						
A	1	1 3/16	32.75	33.38	6.18	44.69
B	1	1 3/16	32.63	33.13	6.18	44.69
Panels VII						
A	1 1/4	1 1/4	32.44	32.44	0	0
B	1 1/4	1 1/4	32.38	32.38	0	0
Panels VIII						
A	7/8	1 1/16	29.19	33.96	5.77	41.20
B	7/8	1 1/16	28.31	33.47	5.77	41.20
Panels IX						
A	7/8	1 1/16	28.88	33.64	5.77	41.20
B	7/8	1 1/16	29.44	34.09	5.77	41.20
Panels X						
A	1	1	33.88	33.88	6.18	44.69
B	1	1	34.06	34.06	6.18	44.69

\* NM=Not Measured

TABLE 5

Results of Impact and Compression Tests

Panels III, IV, VI, VII, IX, X

	Integrated Areas ft-lb-gal/hr		Average of Areas ft-lb-gal/hr	Mortar Compressive Strength psi
	Series 1	Series 2		
Panels III				
A		1830	2310	9567
B	2790			
Panels IV				
A		11908	11292	9342
B	10676			
Panels VI				
A	6780		6615	9292
B		6450		
Panels VII				
A	0		0	9792
B	0			
Panels IX				
A	14628		12450	8975
B		10272		
Panels X				
A		2300	2450	9525
B	2600			

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FLOW FOR 600 in. lbs ENERGY ABSORPTION, liters

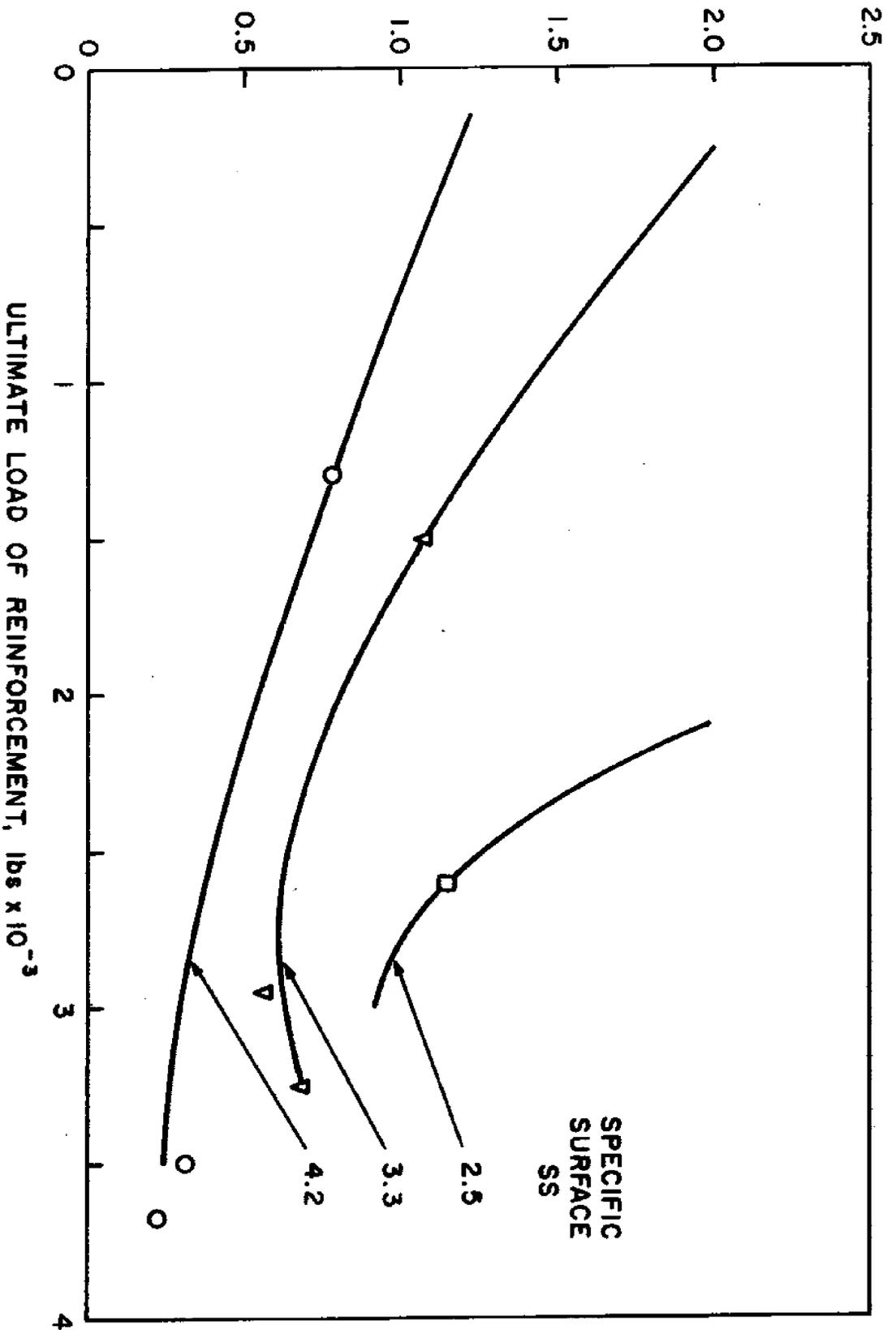


FIGURE 1.

EFFECT OF SPECIFIC SURFACE AND DUCTILITY OF REINFORCEMENT ON IMPACT DAMAGE. [FROM (29).]

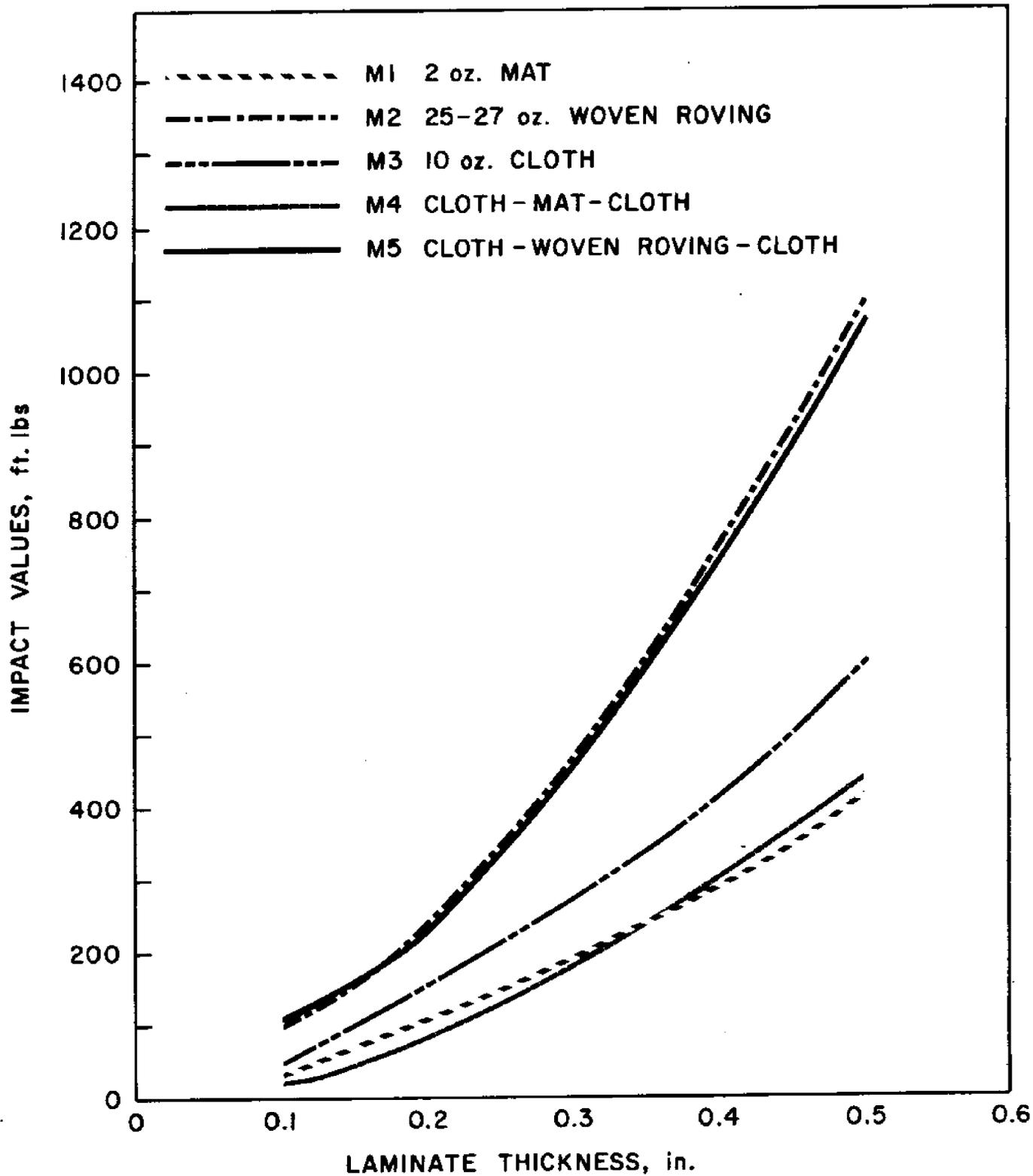


FIGURE 2.  
 IMPACT VALUES OF FRP (POLYESTER) LAMINATES  
 IN THE CRITICAL CONDITION. [FROM (10).]

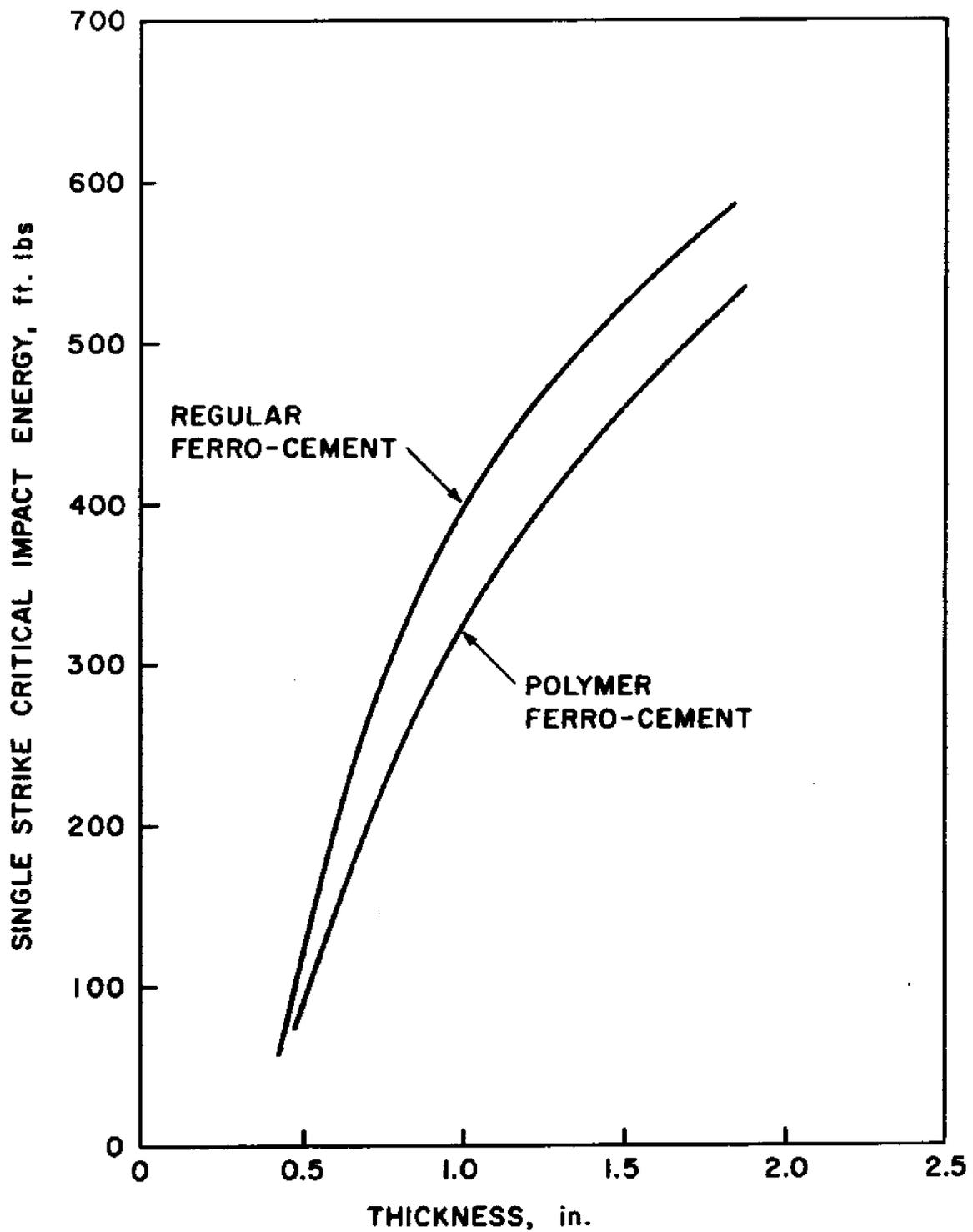


FIGURE 3.

IMPACT VALUES OF REGULAR AND POLYMER FERRO-CEMENT PANELS IN THE CRITICAL CONDITION. [FROM (5).]

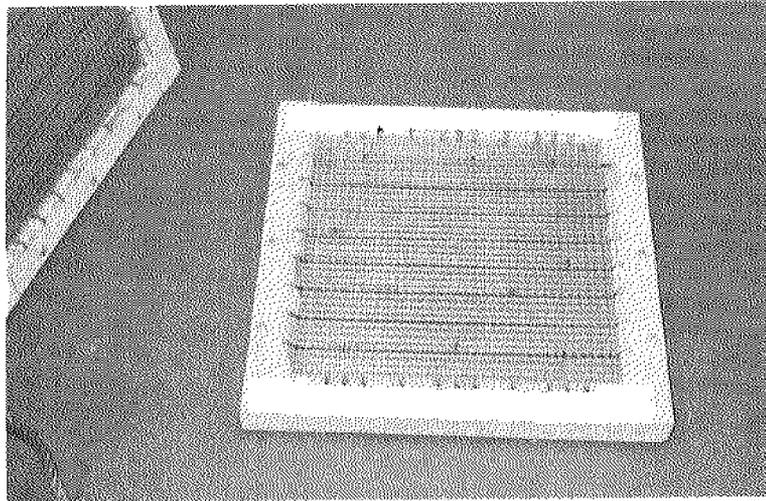


FIGURE 4.  
MOLD AND REINFORCEMENT  
READY FOR POURING.

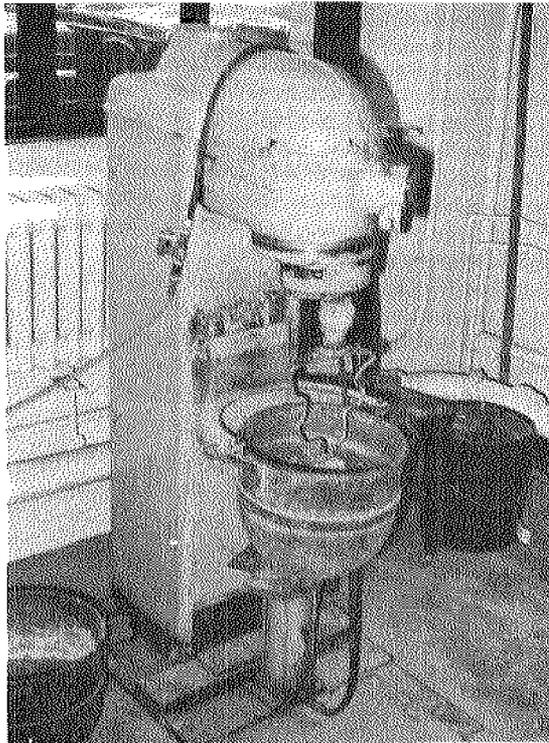


FIGURE 5.  
CEMENT MIXER.

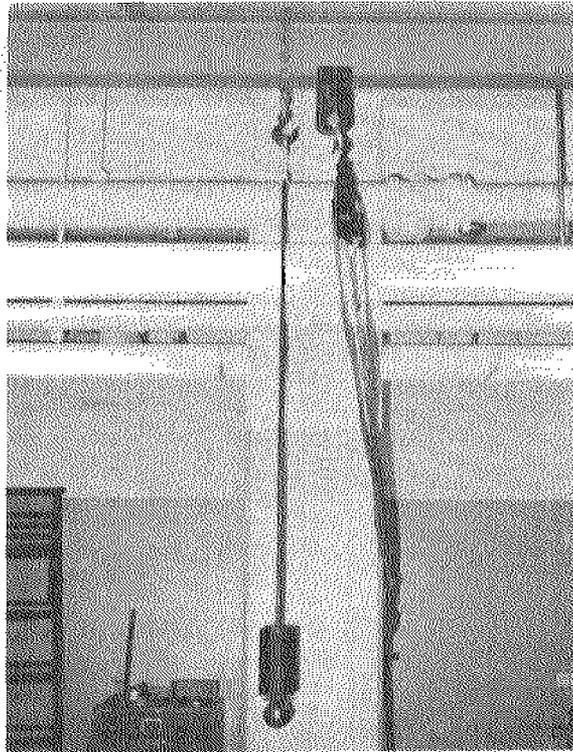


FIGURE 6.  
PROJECTILE WITH WEIGHTS  
READY FOR DROP.

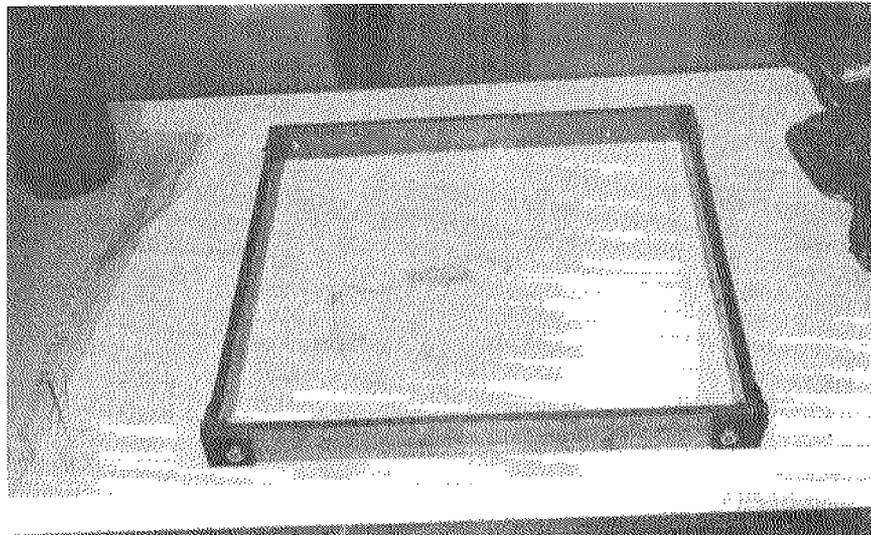


FIGURE 7.  
SUPPORT STAND.

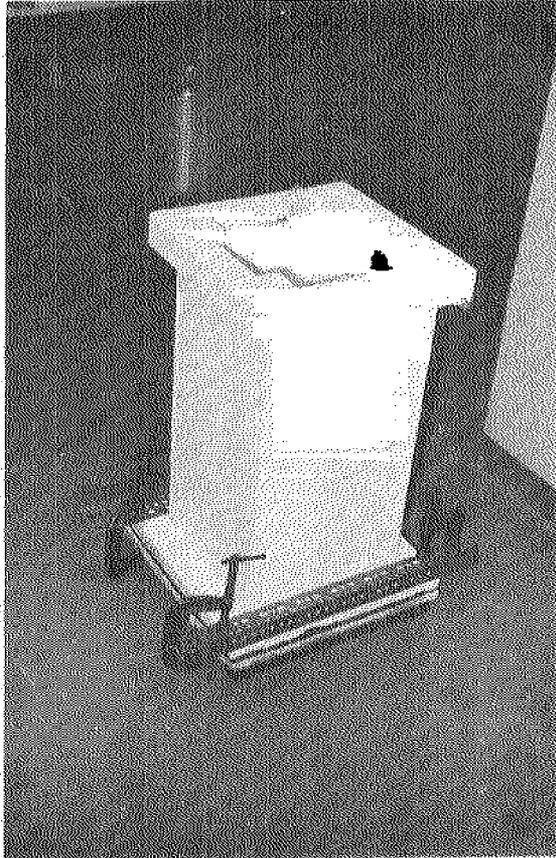
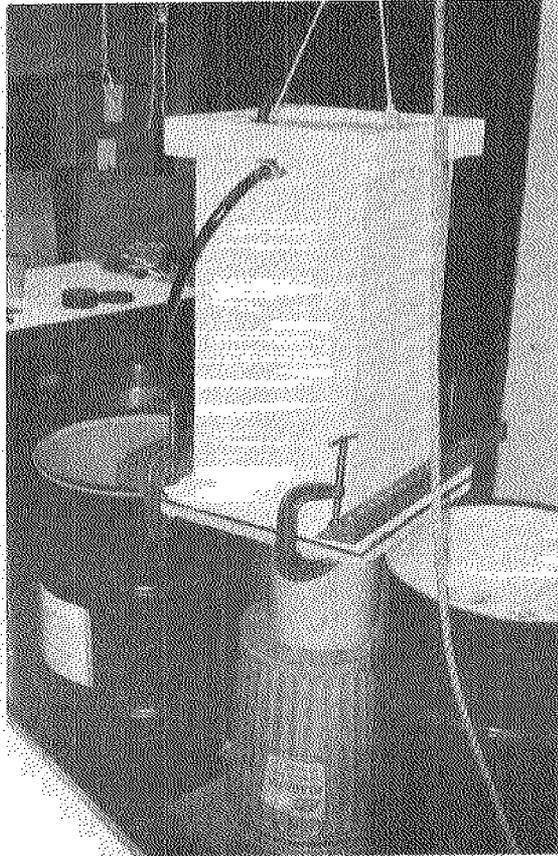


FIGURE 8.  
SPECIMEN WITH WATER BOX ON SUPPORT  
STAND READY FOR DROP.



**FIGURE 9.**  
**SPECIMEN AND WATER BOX**  
**DURING LEAKAGE TEST.**

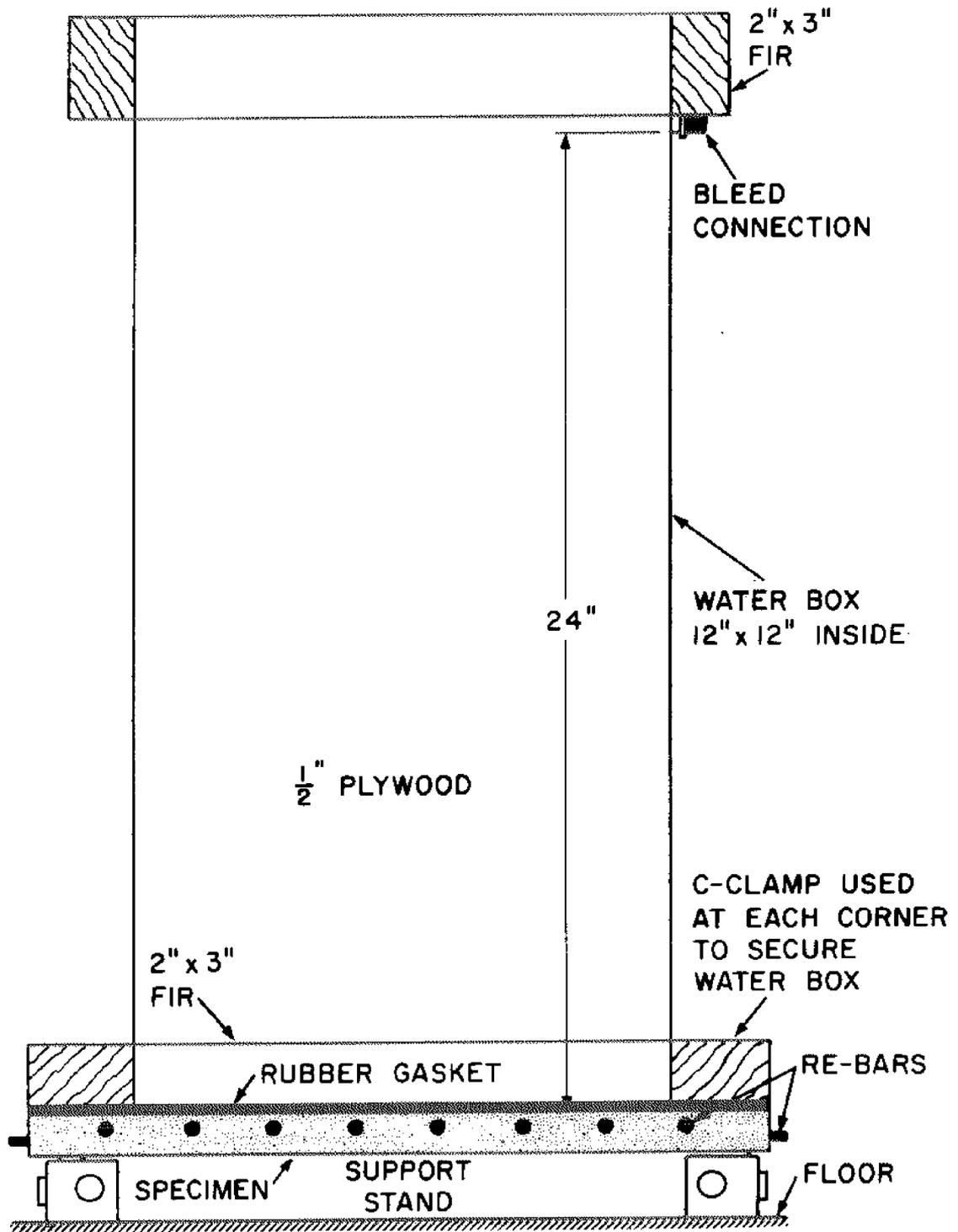


FIGURE 10.  
TEST SET-UP.

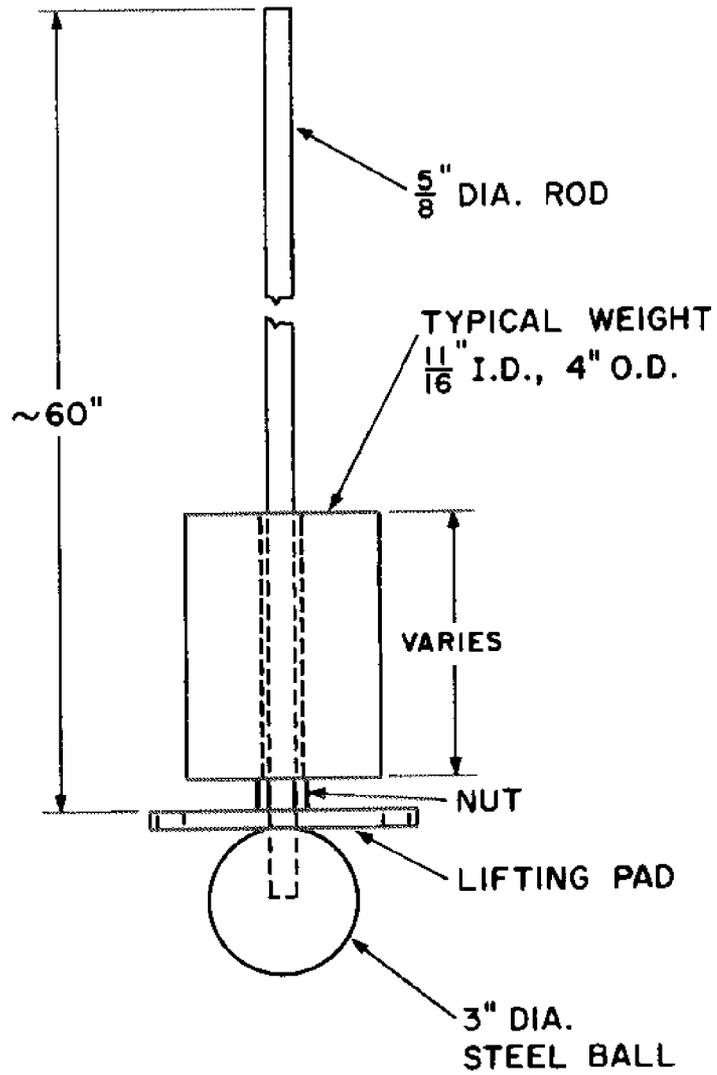


FIGURE 11.  
PROJECTILE.

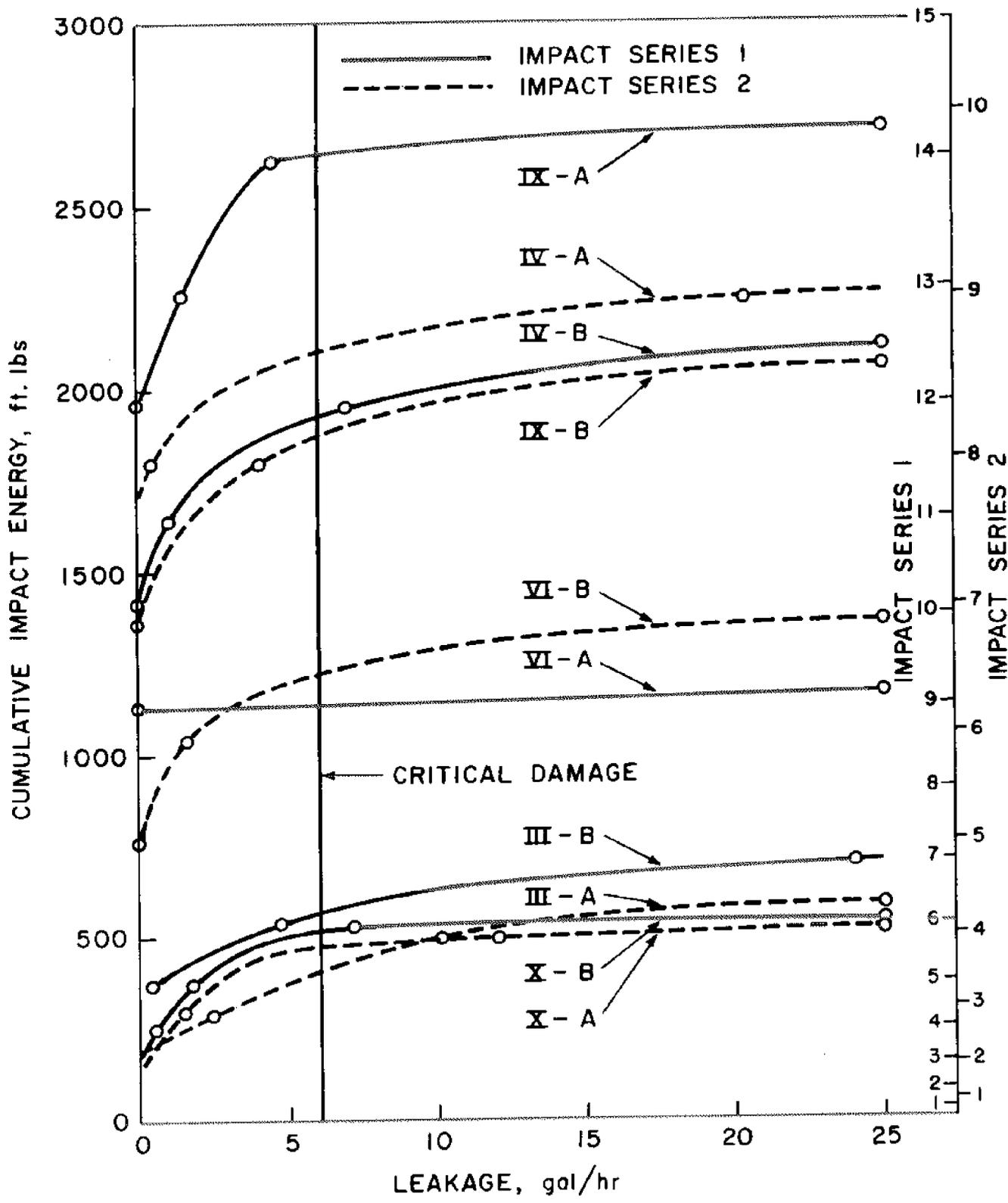


FIGURE 12.  
LEAKAGE vs. CUMULATIVE IMPACT ENERGY  
FOR PANELS III, IV, VI, IX, X.

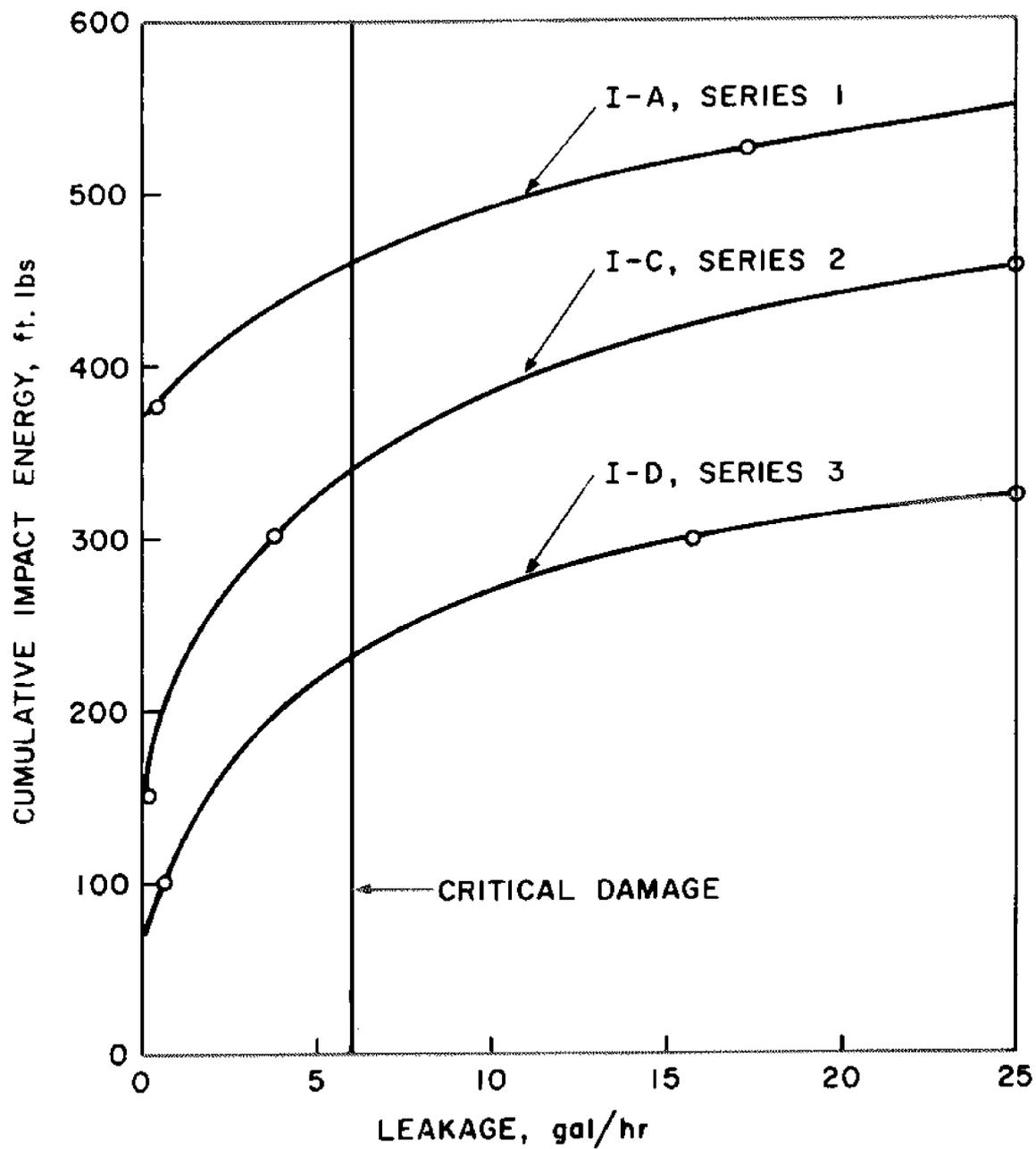


FIGURE 13.

PANELS I. LEAKAGE vs. CUMULATIVE IMPACT ENERGY.  
 [SEE ALSO FIGURE 14.]

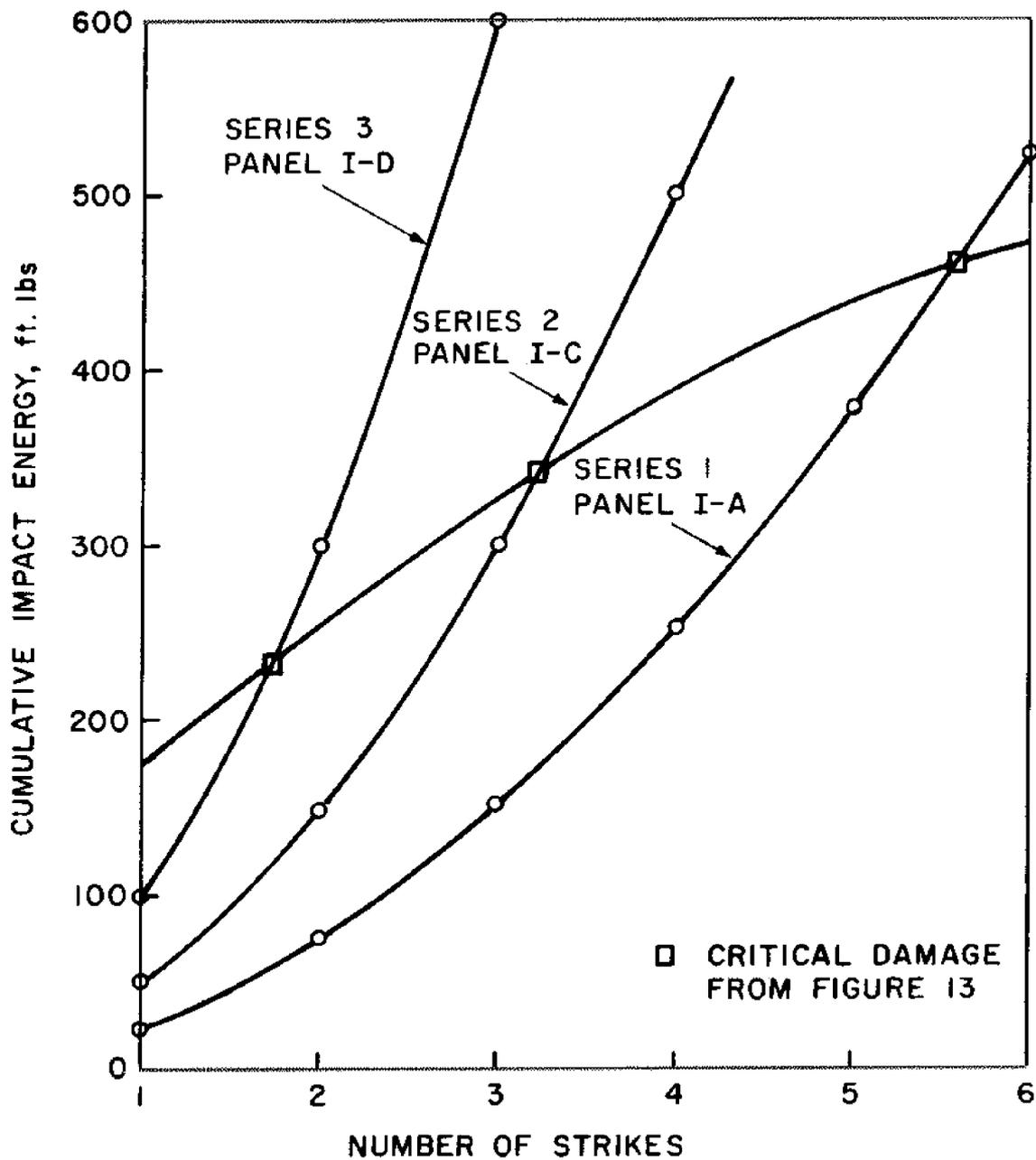


FIGURE 14.

PANELS I. NUMBER OF STRIKES vs. CUMULATIVE IMPACT ENERGY. [SEE ALSO FIGURE 13.]

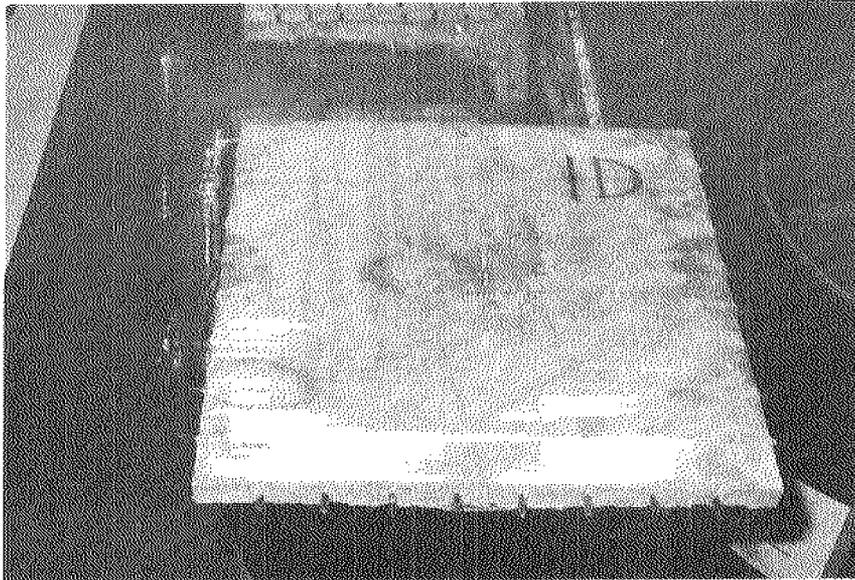


FIGURE 15.  
TYPICAL BOTTOM DAMAGE.

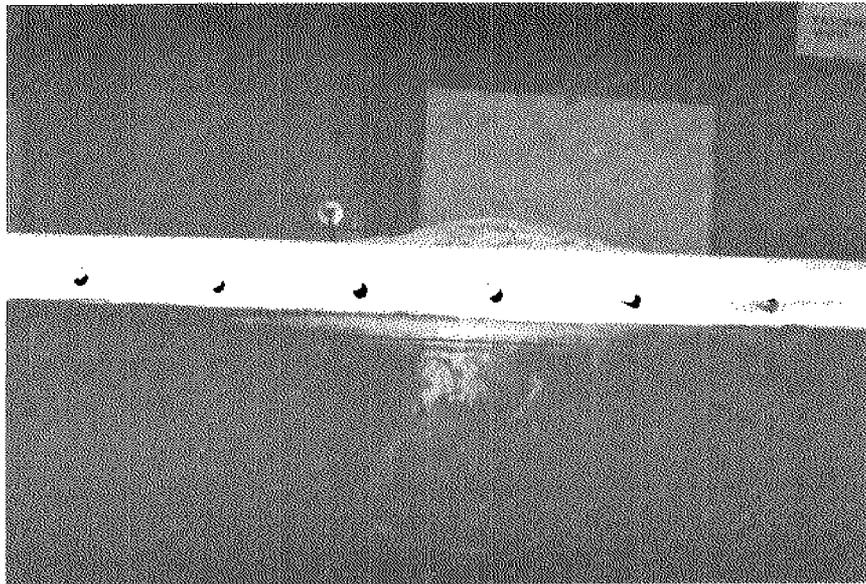
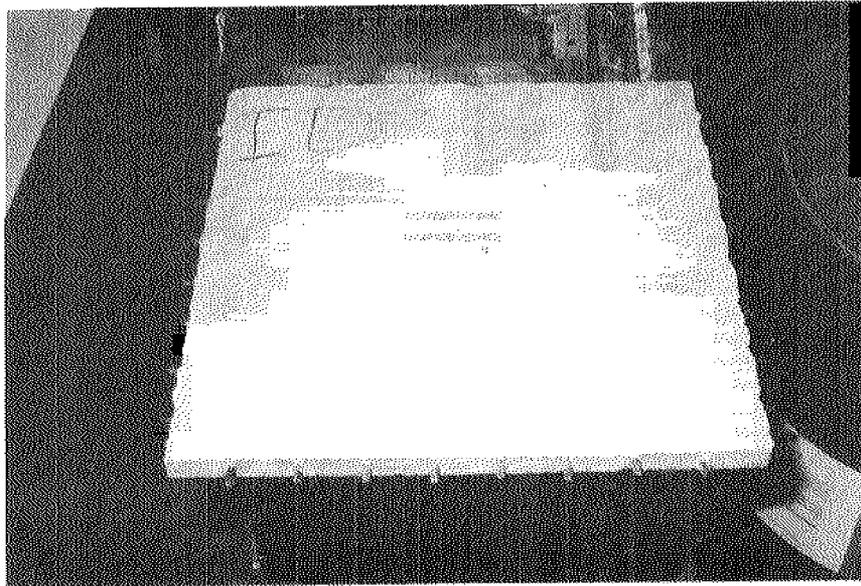


FIGURE 16.  
TYPICAL BOTTOM DAMAGE, EDGE VIEW.



**FIGURE 17.**  
**TYPICAL TOP DAMAGE.**

APPENDIX A

Test Data

TEST DATA

Panels I

Panel I-A

Impact Series 1

Strike	Weight lb	Height in	Energy ft-lb	Cum. Energy ft-lb	Leakage gal/hr (1)(2)	Damage	
						Top (1)(3)	Bottom (1)(4)
1	9.44	32.00	25	25	NM	1/4	NM
2	10.57	56.75	50	75	NM	3/4	NM
3	21.72	55.25	100*	175	0	1 1/4	5 1/2x1/4
4	26.97	55.75	125	300	0.36	1 3/4	5 1/2x1/2
5	32.13	56.00	150	450	17.2	2	6x5/8

\*75 ft-lbs inadvertently omitted

Panel I-C

Impact Series 2

1	10.57	56.75	50	50	NM	NM	NM
2	21.72	55.25	100	150	0.23	1 1/4	5x1/4
3	32.13	56.00	150	300	3.75	1 3/4	6 1/2x1/2
4	43.30	55.50	200	500	40	2 1/2	7 1/2x3/4

Panel I-D

Impact Series 3

1	21.72	55.25	100	100	0.63	1	5x1/8
2	43.30	55.50	200	300	15.8	2	6 1/2x5/8
3	64.74	55.25	298	598	152	3	8x1 1/8

Panel I-B

Single Strike Impact

1	38.11	55.25	175	175	0.05	1 1/2	5x3/8
---	-------	-------	-----	-----	------	-------	-------

Continued

TEST DATA  
Panels I (Cont)

Compressive Strength

2" cubes:

Panels I-A & I-B: 9150 psi 9525 psi 8750 psi Mean: 9142 psi

Panels I-C & I-D: 9975 psi 9875 psi 9975 psi Mean: 9942 psi

Notes.

- (1) NM = Not measured
- (2) Hourly leakage based on 15 minute measurement
- (3) Top damage is the diameter of the indentation in inches.
- (4) Bottom damage is the diameter x height of the bulge in inches.

TEST DATA

Panels III

Panel III-B            Weight--31.31 lbs.

Impact Series 1

Strike	Weight lb	Height in	Energy ft-lb	Cum. Energy ft-lb	Leakage gal/hr (1)(2)	Damage	
						Top (1)(3)	Bottom (1)(4)
1	9.44	31.75	25	25	NM	NM	NM
2	10.57	55.75	49	74	NM	1/2	0
3	15.82	56.75	75	149	NM	5/8	0
4	21.72	55.25	100	249	0	1	4x1/8
5	26.97	55.75	125	374	0.44	1 1/2	5x1/4
6	32.13	56.00	150	524	4.9	2	6x3/8
7	38.11	55.25	175	699	24	2 1/4	6x5/8

Panel III-A            Weight--32.38 lbs.

Impact Series 2

1	10.57	56.50	50	50	NM	NM	NM
2	21.72	55.75	101	151	0	3/4	4" $\phi$ crack
3	32.13	56.00	150	301	2.62	1 1/2	4 3/4x1/4
4	43.30	55.50	200	501	10	2 1/4	5 1/2x1/2
5	53.49	56.10	250	751	54	2 1/2	7x7/8

Compressive Strength

2" cubes:    9625 psi    9500 psi    9575 psi    Mean: 9567 psi

Notes

- (1) NM = Not measured
- (2) Hourly leakage based on 15 minute measurement
- (3) Top damage is the diameter of the indentation in inches.
- (4) Bottom damage is the diameter x height of the bulge in inches.

TEST DATA

Panels IV

FRP (polyester) facing on near side

Panel IV-B            Weight before facing--28.12 lbs.  
                           Weight after facing---32.61 lbs.

Impact Series 1

Strike	Weight lb	Height in	Energy ft-lb	Cum. Energy ft-lb	Leakage gal/hr (1)	Damage Top (1)	Bottom (1)(4)
1	9.44	31.75	25	25	NM	0	NM
2	10.57	56.75	50	75	NM	3/4	cracks
3	15.82	56.60	75	150	NM	1 1/4	cracks
4	21.72	55.50	100	250	0	1 5/8	3 3/4x1/8
5	26.97	55.50	125	375	0	2 1/8	4x1/8
6	32.13	55.75	149	524	0	2 1/2	4 1/2x3/8
7	38.11	54.75	174	698	0	2 3/4	4 1/2x1/2
8	43.30	55.25	199	897	NM	3	4 1/2x5/8
9	48.30	55.80	225	1122	0	3	4 3/4x5/8
10	53.55	56.00	250	1372	0.005	1 1/2	5x3/4
11	58.61	56.00	274	1646	0.96	2	5 1/2x7/8
12	64.74	55.75	301	1947	7.0	2 1/4	7x1
13	69.99	55.75	325	2272	42.4	3	8x1 1/8

facing debonded; point of separation not determined

Panel IV-A            Weight before facing--28.88 lbs.  
                           Weight after facing---33.48 lbs.

Impact Series 2

1	10.57	56.25	50	50	NM	1/2	NM
2	21.72	55.25	100	150	NM	1	cracks
3	32.13	56.00	150	300	NM	1 3/4	4x1/4
4	43.30	55.50	200	500	NM	2 1/2	4 1/2x1/2
5	53.55	56.00	250	750	0	2 1/2	5x1/2
6	64.74	55.60	300	1050	0	2	5x3/4
7	75.88	55.35	350	1400	moist	2	6x3/4
8	86.19	55.60	400	1800	0.44	2 1/4	7x7/8
9	97.44	55.60	451	2251	20.2	2 3/4	8 1/2x1 1/8

facing debonded; point of separation not determined

Continued

TEST DATA

Panels IV (Cont)

Compressive Strength

2" cubes: 9300 psi 9725 psi 9000 psi Mean: 9342 psi

Notes

- (1) NM = Not measured
- (2) Hourly leakage based on 15 minute measurement
- (3) Top damage for series 1, strikes 1-9 and series 2, strikes 1-5 is the diameter of the crazed area in inches. Top damage for series 1, strikes 10-13 and series 2, strikes 6-9 is the diameter of the crushed indented area in inches.
- (4) Bottom damage is the diameter x height of the bulge in inches.

TEST DATA

Panels VI  
Rubber facing on far side

Panel VI-A            Weight before facing--32.75 lbs.  
                          Weight after facing---33.38 lbs.

Impact Series 1

Strike	Weight lb	Height in	Energy ft-lb	Cum. Energy ft-lb	Leakage gal/hr (1)(2)	Damage	
						Top (1)(3)	Bottom (1)(4)
1	9.44	32.00	25	25	NM	NM	NM
2	10.57	56.75	50	75	NM	NM	NM
3	15.82	56.75	75	150	NM	NM	NM
4	21.72	55.25	100	250	NM	1 1/4	4x3/16
5	26.97	55.75	125	375	NM	1 1/2	4 1/2x1/4
6	32.13	56.00	150	525	0	2	5x7/16
7	38.11	55.00	175	700	NM	2 1/8	5 1/2x9/16
8	43.30	55.25	199	899	NM	2 3/8	5 1/2x3/4
9	48.30	56.00	225	1124	0	2 5/8	6x1
					(bubbles)		
10	53.55	56.00	250	1374	142 (8 min)	3	6 1/2x1 1/4

Panel VI-B            Weight before facing--32.63 lbs.  
                          Weight after facing---33.13 lbs.

Impact Series 2

1	10.57	56.25	50	50	NM	NM	NM
2	21.57	55.00	100	150	NM	1	NM
3	32.13	56.00	150	300	NM	1 1/2	4x1/4
4	43.30	55.25	199	499	NM	2	5x1/2
5	53.55	56.25	251	750	0	2 1/2	6x3/4
6	64.74	55.50	299	1049	1.5	3	6x1 1/8
7	75.88	55.35	350	1399	28	3 1/4	6 1/2x1 1/4

Compressive Strength

2" cubes:    9500 psi    9500 psi    8875 psi            Mean: 9292 psi

Notes

- (1) NM = Not measured
- (2) Hourly leakage based on 15 minute measurement except as noted
- (3) Top damage is the diameter of the indentation in inches.
- (4) Bottom damage is the diameter x height of the bulge in inches.

TEST DATA

Panels VII  
Unreinforced Concrete

Both panels were completely shattered by a single impact of 25 ft-lbs. A weight of 9.44 lbs. at a height of 31.75 inches was used.

Panel VII-A            Weight--32.44 lbs.

Panel VII-B            Weight--32.38 lbs.

Compressive Strength

2" cubes:    9500 psi    10,275 psi    9600 psi    Mean: 9792 psi

TEST DATA

Panels VIII

FRP (epoxy) facing on far side

Panel VIII-A      Weight before facing--29.19 lbs.  
 Weight after facing---33.96 lbs.

Impact Series 1

Strike	Weight lb	Height in	Energy ft-lb	Cum. Energy ft-lb	Leakage gal/hr	Damage	
						Top (1)	Bottom (2)
1	9.44	31.75	25	25	NM	NM	NM
2	10.57	56.75	50	75	NM	NM	NM
3	15.82	56.50	74	149	NM	7/8	0
4	21.72	55.25	100	249	NM	1 1/4	NM
5	26.97	55.50	125	374	NM	1 5/8	0
6	32.13	55.75	149	523	NM	2	NM
7	38.11	55.00	175	698	NM	2	1" dia. craze facing debonded

Panel VIII-B      Weight before facing--28.31 lbs.  
 Weight after facing---33.47 lbs.

Impact Series 2

1	10.57	56.25	50	50	NM	NM	NM
2	21.72	55.25	100	150	NM	1 3/8	1 1/2" dia. craze
3	32.13	55.75	149	299	NM	1 3/4	2" dia. craze facing debonded

Compressive Strength

2" cubes:    9500 psi    9225 psi    8625 psi    Mean: 9117 psi

Notes

- (1) NM = Not measured
- (2) Top damage is the diameter of the indentation in inches.

TEST DATA

Panels IX  
FRP (epoxy) facing on near side

Panel IX-A                      Weight before facing--28.88 lbs.  
   Weight after facing---33.64 lbs.

Impact Series 1

Strike	Weight lb	Height in	Energy ft-lb	Cum. Energy ft-lb	Leakage gal/hr (1)(2)	Damage	
						Top (1)(3)	Bottom (1)(4)
1	9.44	32.00	25	25	NM	NM	NM
2	10.57	56.75	50	75	NM	NM	0
3	15.82	56.75	75	150	NM	3/4	4" $\emptyset$ crack
4	21.72	55.25	100	250	NM	1 1/2	4 1/2x1/8
5	26.97	55.60	125	375	NM	2	4 1/2x1/4
6	32.13	56.00	150	525	NM	2	5x3/8
7	38.11	55.25	175	700	NM	2 1/4	5x3/8
8	43.30	55.50	200	900	NM	2 1/2	5x3/8
9	48.30	55.80	225	1125	0	2 1/2	5 1/2x3/8
10	53.55	56.00	250	1375	0	2 3/4	6 1/2x5/8
11	58.61	56.25	275	1650	0	1 1/2	6 1/2x3/4
12	64.74	55.60	300	1950	0.05	2	6 1/2x7/8
13	69.99	55.80	325	2275	1.50	2 1/4	6 1/2x1
14	75.88	55.50	351	2626	4.30	2 1/2	7 1/2x1 1/8
15	80.94	55.75	376	3002	99 (5 min)	2 3/4	8x1 1/4
16	86.19	55.50	399	3401	NM	3	8 1/4x1 3/8

Panel IX-B                      Weight before facing--29.44 lbs.  
   Weight after facing---34.09 lbs.

Impact Series 2

1	10.57	56.50	50	50	NM	NM	NM
2	21.72	55.25	100	150	NM	1	4" $\emptyset$ crack
3	32.13	56.10	150	300	NM	1 1/2	3 1/2x1/8
4	43.30	55.50	200	500	NM	2 1/8	4x3/8
5	53.55	56.10	250	750	NM	2 1/2	5x5/8
6	64.74	55.60	300	1050	NM	3	NM
7	75.88	56.00	354	1404	NM	1 3/4	facing debonded 7x7/8
8	86.19	55.50	399	1803	3.97	2 1/4	8 1/4x1 1/8
9	97.44	55.25	449	2252	37.5 (10 min)	2 3/4	8 3/4x1 1/4

Continued

TEST DATA

Panels IX (Cont)

Compressive Strength

2" cubes: 10,100 psi 8900 psi 7925 psi Mean: 8975 psi

Notes

- (1) NM = Not measured
- (2) Hourly leakage based on 15 minute measurement except as noted
- (3) Top damage for series 1, strikes 1-10 and series 2, strikes 1-6 is the diameter of the crazed area in inches. Top damage for series 1, strikes 11-16 and series 2, strikes 7-9 is the diameter of the crushed indented area in inches.
- (4) Bottom damage is the diameter x height of the bulge in inches.

TEST DATA

Panels X

Panel X-B Weight--33.88 lbs.

Impact Series 1

Strike	Weight lb	Height in	Energy ft-lb	Cum. Energy ft-lb	Leakage gal/hr (1)(2)	Damage	
						Top (1)(3)	Bottom (1)(4)
1	9.44	31.75	25	25	NM	NM	NM
2	10.57	56.75	50	75	NM	NM	2 cracks
3	15.82	57.00	75	150	NM	7/8	4x1/4
4	21.72	55.50	100	250	0.5	1 1/2	4 1/2x1/4
5	26.97	55.75	125	375	1.6	2	5 1/2x1/2
6	32.13	56.02	150	525	7.1	2 1/4	5 1/2x3/4
7	38.11	55.10	175	700	180 (2 min)	2 3/4	6 1/2x7/8

Panel X-A Weight--34.06 lbs.

Impact Series 2

1	10.57	56.75	50	50	NM	NM	NM
2	21.72	55.25	100	150	0	1	4x3/16
3	32.13	56.00	150	300	1.4	1 3/4	5 1/2x1/2
4	43.30	55.10	199	499	12	2 1/4	6x3/4
5	53.55	55.75	249	748	150 (2 min)	2 3/4	6 1/2x1 1/8

Compressive Strength

2" cubes: 8900 psi 9925 psi 9750 psi Mean: 9525 psi

Notes

- (1) NM = Not measured
- (2) Hourly leakage based on 15 minute measurement except as noted
- (3) Top damage is the diameter of the indentation in inches.
- (4) Bottom damage the diameter x height of bulge in inches.

APPENDIX B  
SIEVE ANALYSIS OF AGGREGATE

Size of Sieve	Individual amount retained on sieve -gms-	Individual % retained on sieve	Cumulative % retained on sieve
1 1/2"	0	0	0
3/4"	0	0	0
3/8"	0	0	0
4	0	0	0
8	0	0	0
16	191	20.58	20.58
30	300	32.33	52.91
50	240	25.86	78.77
100	126	13.58	92.35
PAN	71	7.65	-----
<b>TOTAL</b>	<b>928</b>	<b>100.00</b>	<b>244.61</b>

FM = Fineness Modulus =  $\frac{\text{Total}}{100} = 2.45$

