SSC-223

COMPRESSIVE STRENGTH OF SHIP HULL GIRDERS
PART II
STIFFENED PLATES

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1971

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The ultimate strength of a ship's hull girder has been a continuing subject of investigation by the Ship Structure Committee. One project in this all important area investigated the strength of small structural models under various combinations of loads.

This report is the second in a two part series on the compressive strengths of small structural test specimens. This work is being continued in an effort to develop an analytical expression for use by the ship designers.

W. F. REA, III
Rear Admiral U.S. Coast Guard
Chairman, Ship Structure Committee

SSC-223

Final Report

on

Project SR-193, "Small Hull Girder Model"

to the

Ship Structure Committee

COMPRESSIVE STRENGTH OF SHIP HULL GIRDERS
PART II
STIFFENED PLATES

by

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ABSTRACT

This is Part II of a two-part report on a year of investigation into the compressive strength of ship hull girders. This part covers stiffened mild steel plates with a/b = 3 and b/t = 50. Seven tests were conducted on panels and grillages loaded in axial compression in various combinations with transverse membrane compression and normal pressure. In addition, a three-bay girder was tested in pure bending.

One of the prime goals of the project was to determine the strength of plates in grillages and girders as compared to the square tube behavior described in Part I. From an engineering viewpoint there was little difference between the square tube strengths and the strengths of plates in the stiffener-plate configurations. The results revealed an increase in plate strength of 4-1/2 percent compared to the tube test data for uniaxial compression loading without normal pressure, and a reduction of 1 percent when tested in uniaxial compression plus normal pressure. The girder strength was 3.7 percent above the tube strength. The effect of biaxiality may have reduced the longitudinal strengths of the grillages compared to the tube data. However, the reduction could have been a few percent at most. A single panel in uniaxial compression was 7.1 percent stronger than the corresponding tube.

All the studies in this phase were performed on electron-beam-welded plate assemblies of which a 0.030 inch thick mild steel plate was the basic element. The plates between stiffeners were 1.50 inches wide (b/t = 50) and 4.50 inches long (a/b = 3). These nominal dimensions are the same as the plates which comprised the faces of the tubes for b/t = 50 which were tested during the Part I investigation. The stiffeners were designed to insure achievement of maximum plate strength. Strain data were recorded to check stress distributions for general uniformity.

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NOMENCLATURE

Symbols

a	length of plate, in.
b	width of plate, in.
E	Young's modulus, msi (1 msi = 10^6 psi)
P_x	force applied longitudinally, lb.
P_y	force applied transversely, lb.
g	multiplier converting σ_{cy} to σ_e
I	moment of inertia of cross section in.^{4}
k_y	transverse buckling coefficient
ℓ	multiplier for converting plate thickness (t) to effective width of weld tension stress region on one side of weld centerline, in.
N_x	plate longitudinal loading, $t\sigma_x$, lb/in.
N_y	plate transverse loading, $t\sigma_y$, lb/in.
p	pressure acting normal to plate, psi
t	thickness of plate, in.
x	longitudinal coordinate of plate or grillage, in.
y	transverse coordinate of plate or grillage, in.
Z	section modulus, $I/\bar{z}$, in.^{3}
z	coordinate perpendicular to plate, in.
ϵ	axial strain, μ (10^{-6} units)
ν	Poisson's ratio
σ	stress

Subscripts

m	machine-induced
p	pressure
r	residual, or related to residual stress
t	transverse (residual)
u	ultimate
x, y, z	coordinate directions
cy	compressive yield
xu	ultimate in the x direction
yu	ultimate in the y direction

Superscript

–	from centroid

INTRODUCTION

Purpose of Project

The construction of a ship consists of numerous plates joined to comprise a structural unit capable of resisting the various forces imposed by the sea. Modern fabrication practices employ welding which induces residual stresses in the plates before they are subjected to the action of the sea. Therefore, the body of data relevant to plate strength in the presence of residual stresses should provide basic information for predicting the strength of a ship to resist structural instability. On the other hand, there may be complex structural interactions in a ship which might tend to influence the direct application of plate strength data from tube tests when used in conjunction with relatively simple methods of beam stress analysis such as $\sigma = Mz/I$.

This second phase of the hull strength project for this year provided data on the strength of plate elements in a shiplike structure comprised of those elements.

Strain Measurements

The purpose of this investigation was to determine the strengths of various stiffened plate configurations under several combinations of loading. As an aid to insuring that the externally applied loads were being distributed properly to the interiors of the specimens, strain gages were applied in several locations on the grillages and girder. It was not the main purpose of the acquired strain data to function as an experimental mechanics approach to the determination of stresses within the specimens. However, the strain patterns did reveal interesting details of the structural behavior as a function of the load combination and load level.

STIFFENED PLATE STRUCTURAL BEHAVIOR

General Note

The effort of Ref. 1 was on the determination of the strengths of unstiffened plates. The presence of longitudinal and transverse framing would tend to modify the structural behavior of a stiffened plate system compared to an unstiffened plate. These would relate to the effects of welding as well as to the stresses induced in the multiple plate array and to the character of buckling and failure which might be observed.

A frequently mentioned source of difference between ship behavior and single plate action is the continuity of the plates of the ship across the webs of girders, frames and bulkheads. Also, longitudinal stiffeners usually retain bending continuity across frames and bulkheads. An additional feature might be the possible effect upon strength of an alteration in stress distribution from the unbuckled state to the buckled state. The model tests of this project were designed to provide information which would aid in determining the significance of these factors if the tube test data were to be used directly for design with no correction for these factors.

The square tube tests permit accurate control over the load in a plate before and after buckling, and the trepanning procedures identify the magnitude of the residual stress in the plate. Because of the factors mentioned above concern exists that the same control may not be possible on the individual plates which comprise a grillage, either as a separate entity or as one bay of a ship hull girder. For this reason the experimental program for stiffened plates was designed to provide edge support for the grillages which approximated simple support with no continuity to the side walls while the ship structural behavior was reserved for the girder test. In this manner it was hoped to observe the change from plate to grillage and then the change from grillage to ship hull girder.

The preceding comments were directed principally to uniaxial longitudinal compressive strength. Some of the grillages were tested in combined loading to assess the influence of transverse membrane compression and of normal pressure. The tube tests indicated possibly large reductions in longitudinal compressive strength when transverse loads were high for plates with $b/t = 50$. In this case the influence of normal pressure was not important. The grillage tests involved transverse stresses which were considerably smaller than attained in the tube tests because of the limitations of the grillage loading equipment. Nevertheless, it was hoped to gain an initial evaluation of biaxiality on grillage strength.

Welding Residuals

It was demonstrated in Ref. 1 that the weld-induced longitudinal compression in the center of a long plate may be found from the relation

$$\sigma_r/\sigma_{cy} = 2(b/2\ell t - 1) \qquad (1)$$

This relation was used to obtain the theoretical welding residual of 8.2 ksi for $b/t = 50$ which agreed well with the experimental value of 8.5 ksi. It presumably would apply to each plate of a grillage.

However, because of the presence of the transverse frames and bulkheads it also follows that transverse welding residuals are to be expected. To compute those stresses, it is necessary to replace the plate width by the plate length in Eq. (1). If the same values of g and ℓ are retained as for the tube tests (1.25 and 3.5, respectively) then the transverse compression in the midregions of the plates in the grillages would be expected to be of the order of 2.4 ksi.

According to the data displayed in Ref. 1 this would not be expected to induce a significant reduction in the longitudinal strength, although it could reduce the transverse strength. This transverse stress was included in reducing the data from the grillage and girder tests.

Structural Coupling

When loads are applied to a structural system involving a plate stiffened on one side only, membrane loads induce curvature and bending moments induce membrane strains. This action is termed coupling. Application of uniform uniaxial compression to the plates and stiffeners of a grillage would induce a lateral widening equal to the Poisson ratio effect if there were no lateral restraints. At transverse frames and bulkheads, however, the free lateral expansion would be restrained. Several effects would follow. The stiffener flanges and webs midway between the transverses would tend to move laterally which would result in a rolling tendency relative to the laterally restrained ends at the transverses. In addition, the restraints imposed by the transverses would be manifested in the plates as shear stresses which would peak at the four corners of the panel.

The tendency of the plate to expand laterally would induce forces on the transverses at the plate-transverse intersection which would tend to stretch the transverses slightly and also induce a bending action. This would generate compression in the top along the flange as well as bending of the longitudinals in which the flanges would be loaded in compression.

The action of water pressure on the ship bottom would induce longitudinal bending in the plate and stiffeners that would peak in compression at midspan of each panel and in compression in the flanges over the transverses. The bending of the transverse frames would induce transverse compression in the plate. These would induce a stress field in the bottom plates which would be biaxial in nature and would vary throughout the bottom.

The transverse forces in the plane of the bottom plates would induce a direct biaxial compression stress field in the plates. The transverse frames and bulkheads would participate in supporting this transverse force component. Furthermore, the transverse force would vary in a more-or-less linear fashion over the depths of the transverses and in a more complex manner near the bulkheads because of the varying pressure head on the sidewalls. If the ship should be in a rolled attitude, the forces would not be balanced externally but would have to be transmitted internally through the transverse framing, which would lead to significant shear stresses in the plates probably peaking near the outer corners of each panel.

Some of these phenomena were observed in the strain gage data on the grillage and girder tests. However, they all appeared to have no detectable effect on the observed strengths. The significance of this negative result might warrant study in a subsequent investigation. It was not explored herein.

STIFFENED PLATE SPECIMEN DETAILS

The eight specimens tested in this second phase were as given in Table 1.

Table 1 - Stiffened Plate Test Specimens (All Dimensions are Nominal)
All a = 4.5 in., all b = 1.5 in., all t = 0.030 in.

Test	Specimen Description	Loading
1	One panel long, three stiffeners wide	N_x
2	Three panels long, two stiffeners wide	N_x
3	Two panels long, two stiffeners wide (No. 2, shortened and annealed before retest)	N_x
4	Grillage six stiffeners wide	N_x
5	Grillage eight stiffeners wide	N_x, p
6	Grillage eight stiffeners wide	N_x, N_y
7	Grillage eight stiffeners wide	N_x, N_y, p
8	Girder consisting of three grillages each eight stiffeners wide	Bending
Compressive yield strength, σ_{cy} = 39.2 ksi Young's modulus, E = 29.2 msi Poisson's Ratio, ν = 0.28	(The material is the same as in Ref. 1)	

Typical sections and corresponding section properties appear in Fig. 1. The stiffener design details were developed by rational analysis using Vasta's charts (Ref. 2) as a guide. The geometry for each of the seven grillages of this investigation is shown in Fig. 2. Three of the grillages were integrated into the three-bay girder. The other four were tested under various load conditions. An impression of an assembled grillage may be gained from the top views of the 3-grillage array which was tested in the girder investigation (Fig. 3).

Each grillage was built up from three panels of plate length, a, longitudinally stiffened at intervals equal to the width of one plate, b. The panels are delineated by the transverse frames and the end bulkheads. The entire assembly was electron-beam-welded from individual strips for the plates, for the longitudinal stiffener and transverse frame webs, and for the flanges of the longitudinals and transverses.

The electron beam welding process parameters were the same as for the tube tests. The welds were made at 26 kilovolts and 10 milliamperes with the work held 5 inches from the gun at a feed speed of 100 inches/minute. The beam was approximately 0.010 inches wide at the work surface.

LOADING FIXTURES

All the test specimens were loaded in the 25,000 pound testing machine, described in Part 1. Longitudinal compression was applied directly by the crossheads of the machine through load spreaders typical of those used to achieve uniformity. Fig. 4 is a sketch of the spreader system used for longitudinal load application (N_x) as well as the device used to achieve load uniformity for N_y from the 4,000 pound machine, which also was employed in the biaxial studies of Ref. 1.

The shims were employed in the last adjustments before testing of the grillages. This process involved location of the shims, application of a load of the order of 4000 pounds and reading of the strain gages, and final reshimming as required.

A small-scale reproduction of the structural arrangement drawing for the girder experiment appears in Fig. 5. The machine load, F, was halved to each end of the girder. The reactions were 24.0 in. inside the loading tabs so that the bending moment in the center region was (12.0)F in.-lbs. (Fig. 5). The internal details of the girder construction were designed to induce as uniform a stress distribution as possible within a practical length before introduction to the outermost edges of the 3-grillage test region. Photographs of the test arrangement are in Fig. 6.

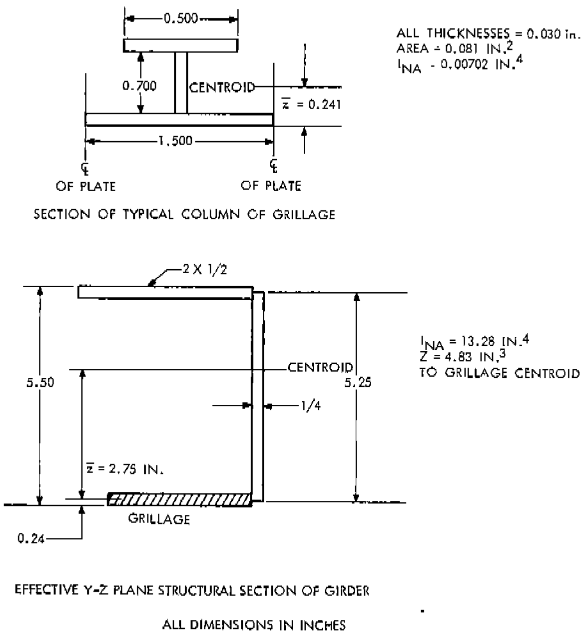


Fig. 1 - Properties of Grillage and Girders

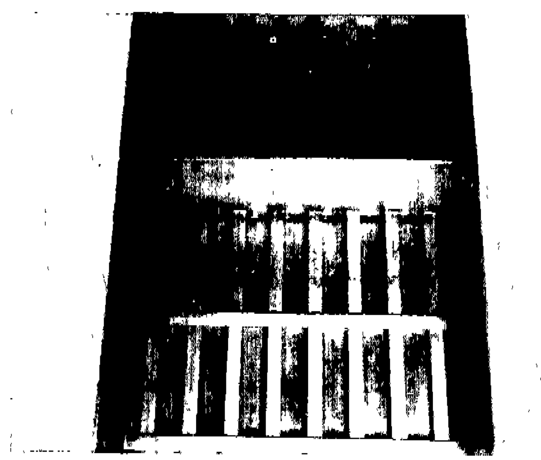


Fig. 3 - Top Views of 3-Grillage Array for Girder Test

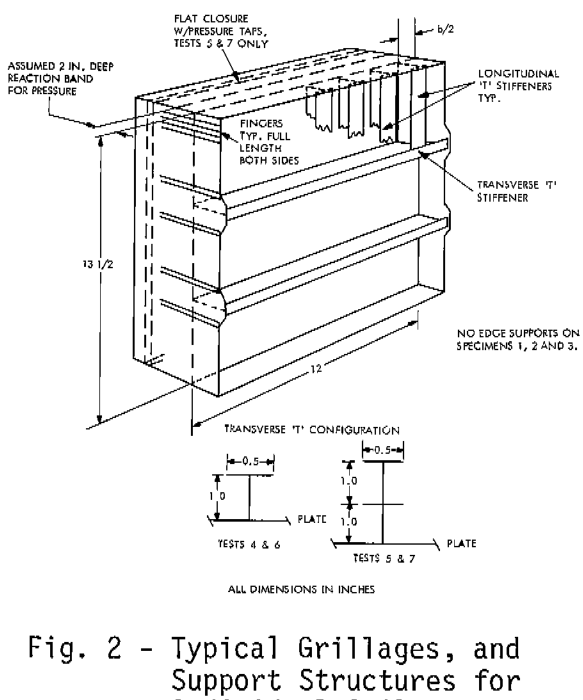


Fig. 2 - Typical Grillages, and Support Structures for Individual Grillage Tests

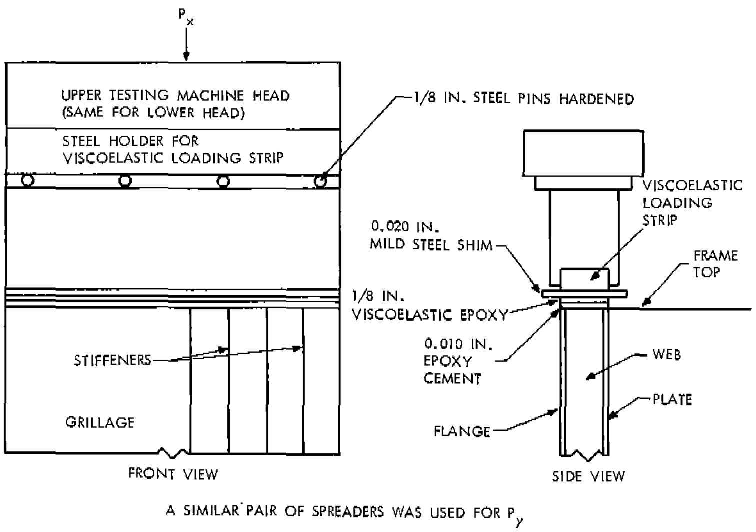


Fig. 4 - Load Spreaders for Grillage Tests

The internal pressure during tests 5 and 7 reacted against the grillage plate over a band estimated to be effectively 2 in. deep (Fig. 2). The vertical force from the 10 psi internal pressure would have been 240 pounds since the two grillages were 12 in. wide. Over the vertical edges the force along 13.5 in. length of the plate would have been 270 pounds. The result of each of these loads would have been a small tension force counteracting the compression from the loading heads. Therefore, the values were subtracted from the total applied loads after computing the machine-induced stresses.

Edge Supports for Grillage Tests

The plate edges parallel to the stiffeners were supported normal to the plane of the plates by fingers welded to the plate and continuous with the back structure of each of the support frames. The amount of longitudinal load which could have been supported by all the fingers was less than 5 percent if both edges of each finger were built-in (Fig. 7) for those on the grillages of tests 4 and 6 on which the finger lengths were 1.1 in., while it was less than 0.8 percent for 5 and 7 on which the fingers were 2.0 in. long. This was determined by a straightforward analysis of the finger system as a series of beams which deflected vertically by an amount dependent upon the nominal axial stress in the grillage and proportional to the distance on either side of the midplane transverse to the stiffener direction. The basis for the analysis appears in Fig. 7.

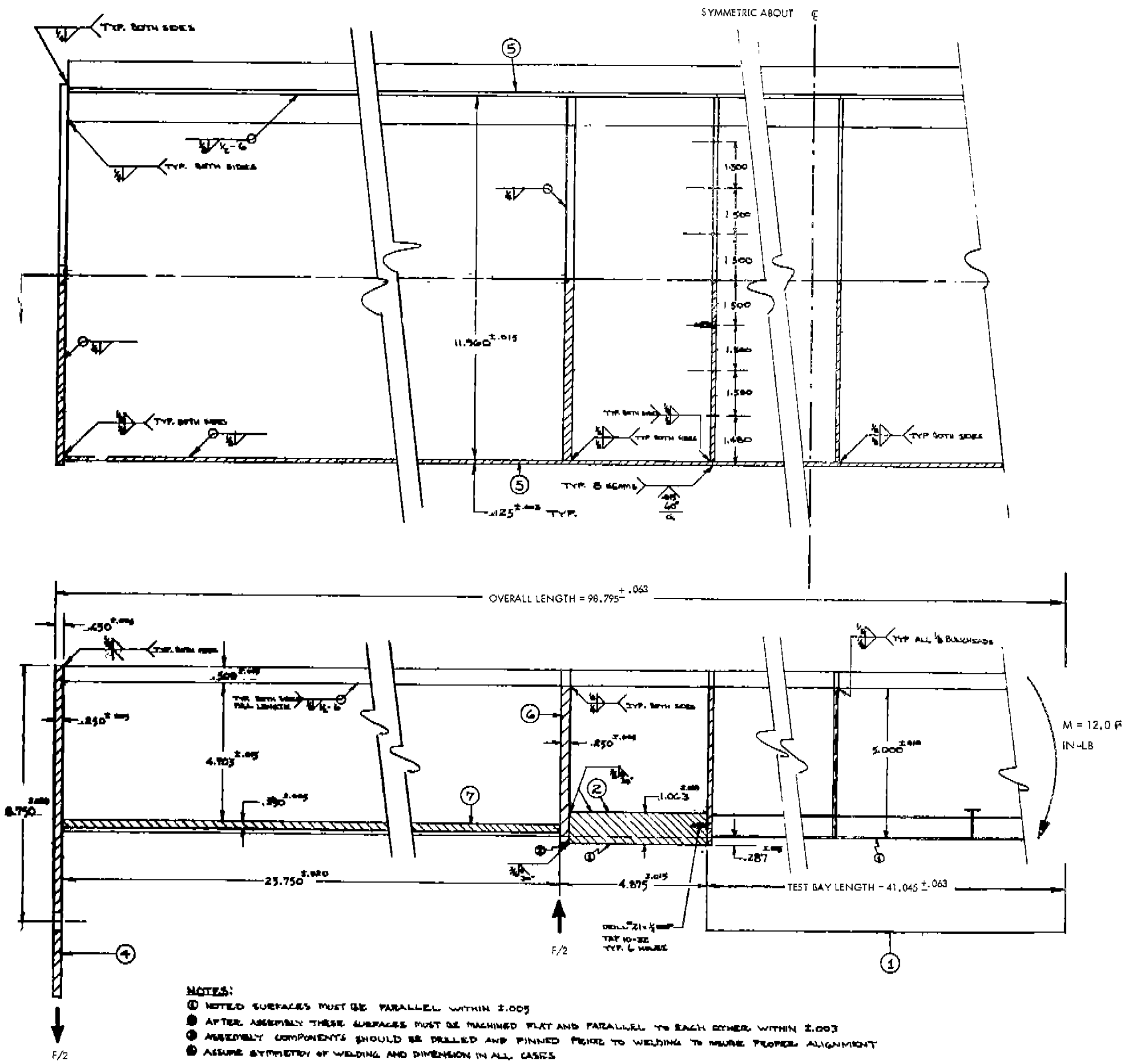
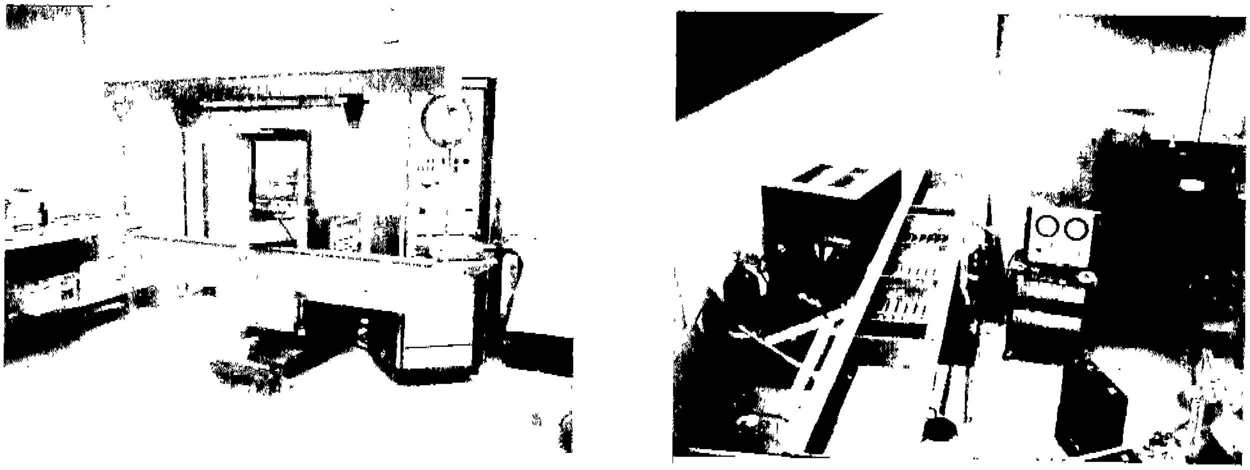


Fig. 5 - Girder Arrangement Drawing

The above values for the maximum amount of finger load probably were too high since completely built in edges were unlikely at the plate-finger attachments. The exact amount would have required an extensive series of measurements on the grillage framing structure and some theoretical interpretation of the results. The framing structure-finger-grillage system is complex. Furthermore, load redistribution occurred within the grillage structure at about 60 percent of failure in all cases. Consequently, the precise value of finger load would have been indeterminate to some extent in spite



a. General View

b. Top View

Fig. 6 - Girder Test Arrangement

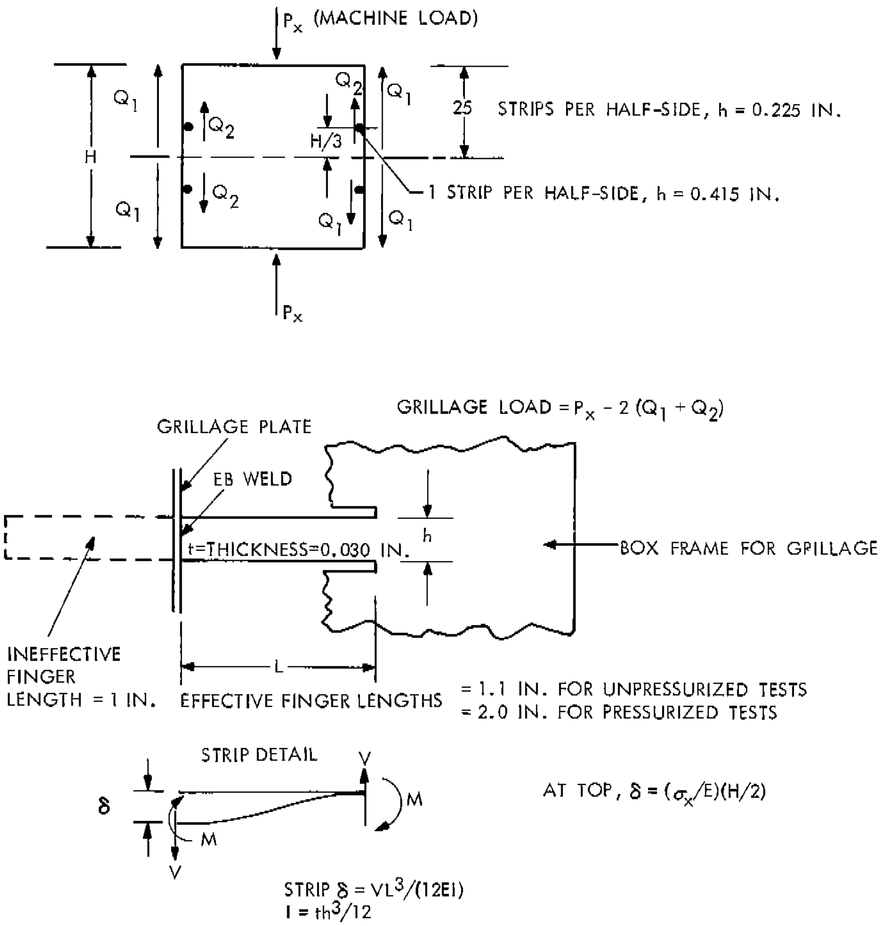


Fig. 7 - Behavior of Grillage Edge Supports

of such analyses. It is estimated that the fingers carried 3 percent of the applied longitudinal load on tests 4 and 6, and no longitudinal load on tests 5 and 7.

In actual construction the fingers extended beyond the plate edges to achieve sound welds and to simplify fabrication.

Experimental Errors

The same dimensional errors for the tube tests apply to the stiffened plate tests since the plates were cut from the same parent plate or from a plate of the same heat. The plate thicknesses and widths averaged less than 1 percent variation from nominal (0.030 inches and 1.50 inches, respectively).

The errors in the maximum longitudinal and transverse compression forces at failure were less than 1/2 percent, and the pressure was of the same order of accuracy. The strain gage errors are considered less than 1 percent.

CORRELATION OF UNSTIFFENED AND STIFFENED PLATE DATA

General Discussion

Table 2 and Figure 8 summarize the results of the 8 tests conducted on stiffened plate structures. As can be seen in Figures 9 through 11, all grillages failed in the loading head panel. The range of stiffened strengths was from 7 percent above the tube results to 1 percent below for uniaxial compression without or with normal pressure applied when the influences of both the weld-induced transverse residual stress and the pressure-induced bending stress on the plate side were taken into account. The tube strength reference test included the presence of longitudinal compression due to the welding.

The results for biaxial loading appeared to lie reasonably close to the trend of the tube data obtained in Ref. 1. Since tube tests were not conducted with precisely the same nominal loading as grillage tests 6 and 7, a more exact comparison cannot be made. On the other hand, it is evident that these results also lie within a 5 percent band of the tube trend.

Effect of Pressure

The longitudinal strain gage data show that when $N_x = N_y = 0$ and pressure was introduced to the N_x, p specimen, 42μ of strain was induced in the plate in the region where failure was observed. This corresponds to 1230 psi (E = 29.2 ksi, Ref. 1), which would be close to the midspan bending stress for simple support over the

Table 2 - Experimental Data for Stiffened Plate Strength Tests

Specimen	Machine-Applied Loads			Derived Data									
	P_x (kips)	P_y (kips)	p[a] (psi)	$P_x - P_{px}$ (kips)	$P_y - P_{py}$ (kips)	A_x (in^2)	A_y (in^2)	σ_{xm} (psi)	σ_{ym} (ksi)	σ_x $\sigma_{xm} + \sigma_b$ (ksi)	σ_x/σ_{xu}	σ_{yu} $\sigma_{ym} + \sigma_{rt}$ (ksi)	k_y
1	6.98	--	--	6.98	--	0.214	--	32.62	--	32.62	1.071		
2	4.66	--	--	4.66	--	0.161	--	28.94	--	28.94	0.950 [b]		
3	4.93	--	--	4.93	--	0.161	--	30.62	--	30.62	1.005		
4	15.50	--	--	15.50	--	0.486	--	31.85	--	31.85	1.045	2.40	0.227
5	18.78	--	10.0	18.54	--	0.641	--	28.92	--	30.15	0.989	2.40	0.227
6	18.13	3.00	--	18.13	2.73	0.648	0.405	27.98	6.74	27.98	0 918	9.14	0.865
7	18.35	3.00	10.0	18.11	2.73	0.648	0.405	27.95	6.74	29.18	0.958	9.14	0.865
8	12.7 (F)							31.62 (2.49F)	--	31.62	1.037	2.40	0.227

a Applied to smooth faces of plates

b Flange-web weld separated and flange buckled

P_{px} = 240 lb (10 psi × 2 in. width × 12 in. length)

P_{py} = 270 lb (10 psi × 2 in. width × 13.5 in. length)

$\sigma_{xm} = (P_x - P_{px})/A_x$

$\sigma_{ym} = (P_y - P_{py})/A_y$

σ_b = 1.23 psi

σ_{xu} = 30.47 psi

σ_{rt} = 2.40 ksi

$k_y = 1.105\ (\sigma_{yu}/E)(b/t)^2$ from Eq. (31) of Ref. 1; E = 29.2 msi

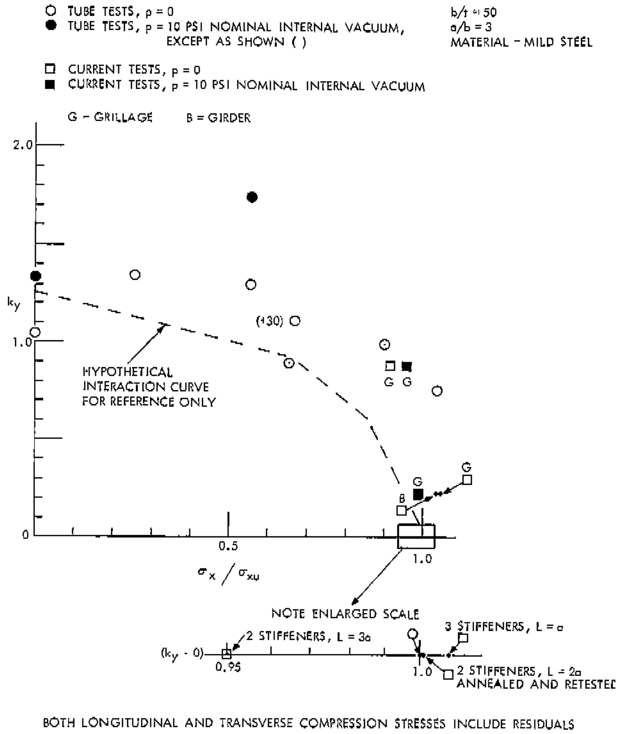


Fig. 8 - Comparison of Unstiffened and Stiffened Plate Data

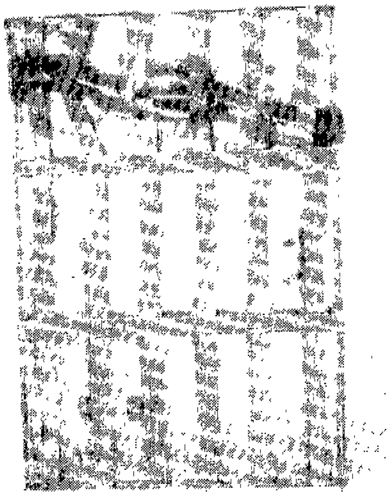
4.5 in. span of each panel for each 1.5 inch of width including the stiffener and plate. As a check,

$$\sigma_b = (1/8)\ pba^2/Z \tag{2}$$

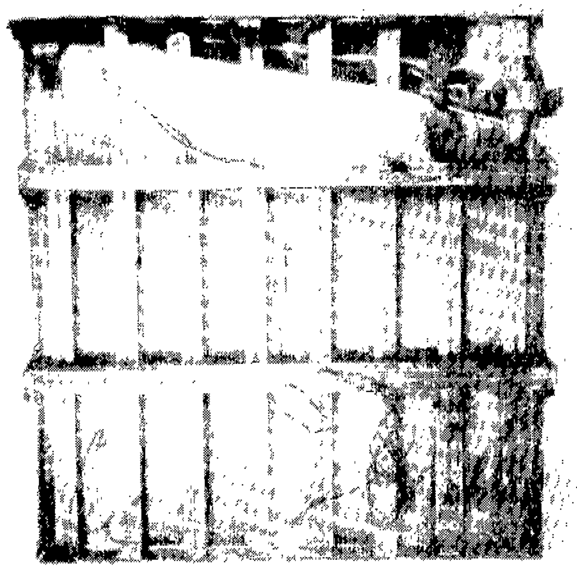
With p = 10 psi, b = 1.5 in., a = 4.5 in. and Z = 0.029 in.^{3}, then the bending stress in the plate is computed to be 1430 psi. The measured value of 1230 psi was used to derive the total specimen failure stresses for the N_x, p and N_x, N_y, p grillages.

The strain gage data also revealed 80μ in the center plate (middle panel). This may have been the result of adding the panel bending stress and the bending stress due to full-span action of the center stiffeners since the transverse frames were not completely rigid. This feature may require subsequent study since, on the basis of nominal axial and bending stresses alone, failure might have been expected in the center panel instead of the end.

During the N_x, N_y, p, grillage test, 10,000 pounds of longitudinal force and 3,000 pounds of transverse force were applied before the pressure was applied. However, the increments for the N_x, p, specimen were essentially the same for N_x = 0 and N_x = 10,000 lb. In view of the presence of N_x and N_y loading, however, it is difficult to draw conclu-

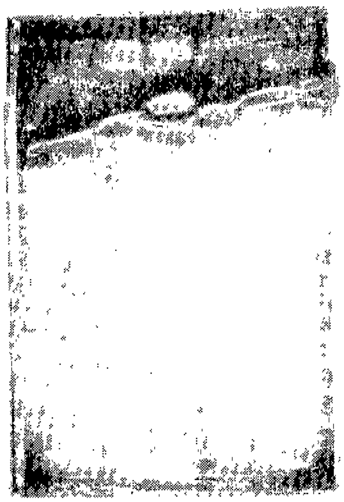


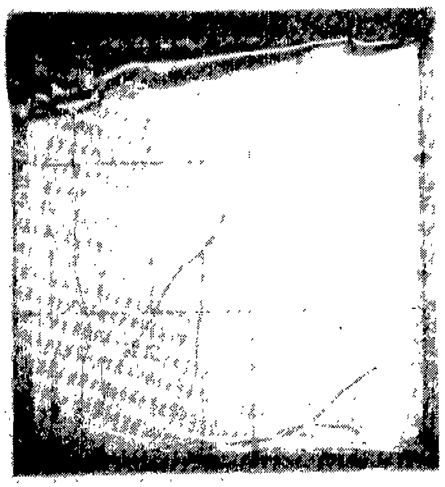
Specimen 4:N_x



Specimen 5:N_x, p

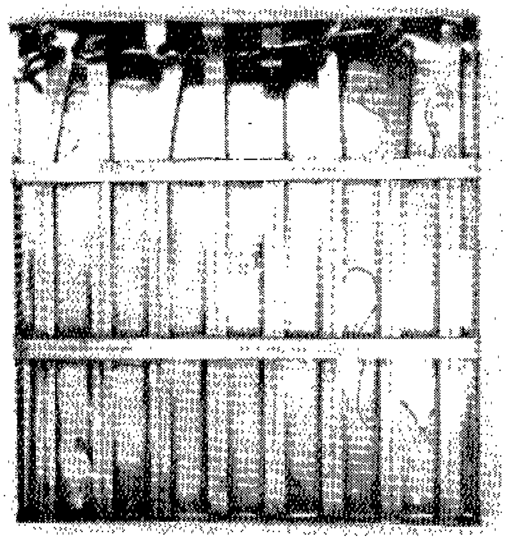
FRONT



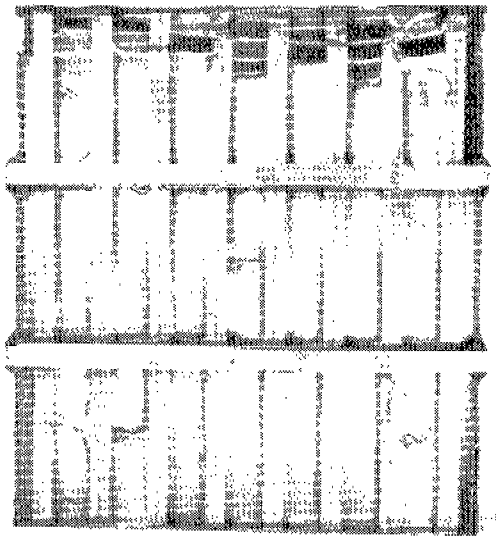


BACK

Fig. 9 - Grillage Failures, N_y = 0. Load Applied to Top and Reacted at Bottom

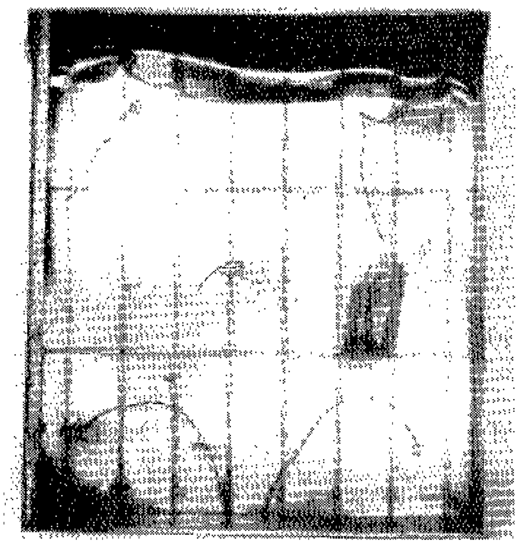


Specimen 6:N_x, N_y



Specimen 7:N_x, N_y, p

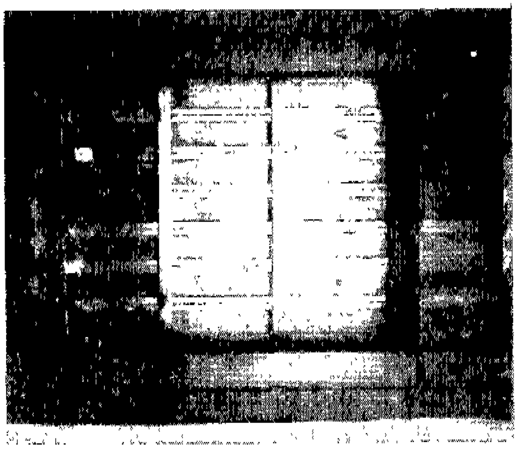
FRONT



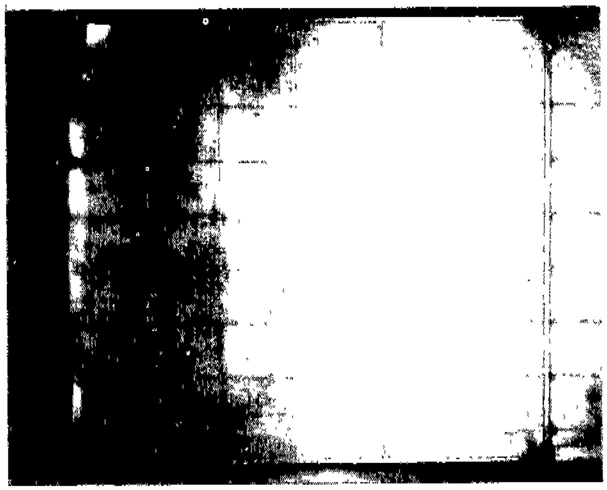
BACK

Fig. 10 - Grillage Failures, N_y > 0. Load Applied to Top and Reacted at Bottom

Specimen 8



View From Above



View From Below

Fig. 11 - Girder Failure, Which Occurred in First Panel of Left End Grillage (Reinforcing Plates Were Removed to Obtain This View).

sions from those results. The biaxiality may have been influencing the results. In this connection it was observed that a large increase in N_y for a given N_x occurred in the tube tests for b/t = 50 when 10 psi vacuum was applied internally. It must be remembered, however, that 1230 psi is only four percent of the failure stress and small details of the model deformation pattern could have influenced the bending stresses. Consequently, in the absence of more reliable information the simply supported panel stress of 1230 psi was employed for the N_x, N_y, p specimen also in calculating the total stress at failure.

Effect of Prior Damage

During the final welding operation of the 3-grillage section of the girder, buckling of several plates occurred. The final welds were cut and most of the plates were observed to return to flatness within 0.002 in. A few plates had a permanent deformation of 0.015 to 0.030 in. These were peened flat before completing the girder construction for testing.

One of the grillages with permanently-buckled and reflattened plates was that in which failure occurred during the girder test. (In fact, several reworked plates were in the end panel where the girder failure was observed). In order to assess the possibility of girder strength loss if that grillage were to be used, a 2-panel-length segment of specimen 2 was flattened and annealed for retest. Permanent buckling had occurred in those two panels during the initial test of specimen 2 when failure occurred in the length that was removed for the retest. As can be observed in Table 2, the damage and rework appeared to have had little deleterious effect. Consequently, it was felt that if the clamping plates were to be added as an additional precaution, the full strength of the girder could be realized. Before failure occurred extensive plate buckling was observed throughout the three grillages in the girder. In fact, the pre-failure configuration of the girder resembled the weld-induced buckle pattern before repair. As the test data indicate, the nominal failure stress was 3.7 percent above the tube test value.

Discussions of Individual Tests (Refer to Table 2 and to Figure 8)

Specimen 1

This was the first stiffened plate specimen fabricated by the vendor. The purpose was to observe the nature of the welding and dimensional tolerances achievable. The test was conducted as an initial check on the realizable strength. It revealed 7.1 percent greater strength than the tube test, which was not out of the realm of plate data scatter for this b/t. As was shown in Part 1, the size of the strength band begins to increase in the region in which plastic buckling and ultimate load carrying capacity begin to match.

There is no scientific explanation offered for the fact that this specimen sustained the greatest stress at failure of all the specimens tested in this series on stiffened plates, or that (except for Specimen 2) all uniaxial longitudinal strengths were observed to equal or exceed the tube strength value.

Specimen 2

This was cut from one edge of an 8-stiffener grillage as an initial check on the general character of the behavior to be expected from a grillage. The slightly lower strength (95 percent of the tube value) was assigned to premature column buckling of part of the flange in one end bay as a result of failure of the weld to the web. As a result a thorough inspection was conducted to insure sound welding of all the flanges. In a few locations the welds were doubtful and the grillages with those defects were returned for rework.

Specimen 3

After the weld-induced buckles were observed to be permanent in a few plates, this retest of a slightly damaged and repaired specimen was felt to be important before reworking and testing the 3-grillage girder. The end bay with the severely crippled plates and stiffeners was removed and the remaining deformations were peened flat to within a few thousandths by eye. The specimen was annealed after which the ends were reground and the retest was conducted. The result (the same strength as the tubes within 1/2 percent) was considered a sound enough basis to proceed with the repair of the grillages for the girder.

Grillages

The results on the individual grillages compared reasonably well to the data obtained in Ref. 1 for tube specimens under polyaxial loading. The strain gage data (which were incidental to the main stream of the investigation) revealed some facets of grillage behavior which could provide a takeoff point for further research, as indicated above.

The two N_x, N_y tests, without and with normal pressure (specimens 6 and 7) are located on Fig. 8 in the same general relation to each other as the two test points for the tubes, $\sigma_x/\sigma_{xu} = 0.56$. That is, the results with pressure are farther from the coordinate origin than the strengths without pressure. The structural basis for these results is not apparent.

Girder

The failure stress at the centroid of the grillage was 3.7 percent above the tube value which is within the range of scatter for the tube test data, and is of the same magnitude as the total experimental error. The strain gages showed a peak plate strain of 638μ at 7750 pounds of machine load (above the tare of 250 pounds at which the zero readings were taken). The corresponding linear extrapolation to failure at 12,700 pounds, with E = 29.2 msi, yields σ = 30.53 ksi, or 0.2 percent above the tube value. It is conceivable that the intermittent $1 \times 1/2$ framing bars at the upper flange may have contributed to this difference between the calculated strength and the strain-extrapolated strength. The flange strains were in approximately the same proportion to the plate strains as the distances from the neutral axis when the stresses were elastic. This might indicate a slightly higher effective section moment of inertia than given in Fig. 1. It also would appear to indicate the use of the distance to the plate centroid instead of to the grillage centroid in calculating the section modulus.

CONCLUSIONS

The following conclusions probably are generally applicable. As in Part I the current tests were conducted on stiffened flat plates of nominal thickness equal to 0.030 in. and nominal width equal to 1.5 in. The plates were fabricated to a/b = 3 from a typically elastic-plastic steel.

1. The results of polyaxial tests on square tubes (Ref. 1), and now on single panels, grillages, and a 3-grillage-girder, appear to yield the same value of plate strength within 7 percent. It was necessary to take proper account of residual stresses in the longitudinal and transverse directions, and of the additional stresses induced by bending from the normal pressure loading, in order to achieve the indicated agreement. This conclusion is essentially the same as that advanced by Vasta in 1938 (Ref.3) for N_x alone.

2. Nominal ultimate load may be used for the strength of a stiffened plate system despite the fact that the structural behavior of a stiffened plate system with stiffening on one side of the plate induces a complex internal stress distribution at loads less than 60 percent of ultimate. The complexities do not appear to influence the strength. The change in stress distribution which occurred at 60 percent of ultimate apparently smoothed the stress field. It is to be expected that redistributions for other b/t systems may occur at different percentages of the ultimate and in a different manner than was observed in these studies.

3. There is an indication of anomalous behavior for b/t = 50 when N_x, N_y and p are applied simultaneously. The apparent increase in load carrying capacity as noted in two tube tests also was observed in a grillage test. An explanation still is required.

4. The square tube data provided the basis for the semi-empirical theory used to design the grillages and girders of this investigation.

RECOMMENDATIONS

1. The square tube investigations and the reinforced plate studies all were conducted on essentially imperfection-free structures. The preliminary result of this investigation relating to strength of damaged-and-repaired plates is hardly basis for a design procedure although it indicates that the strength loss for a properly repaired ship may be slight. It appears worthwhile to consider utilization of the undamaged plates of the tested grillages

to investigate the effects of imperfections of various magnitudes and shapes, and then to assess the effect of repairing those types of imperfections. This would provide data on the strengths for the undamaged structure (from this investigation), for the damaged but unrepaired structure, and finally the strength of the damaged and repaired structure. If this information is correlated with tube tests, as recommended in Part I, then a design procedure should be identifiable.

2. The results of this year of study have shown the usefulness of tube data for predicting the strength of a shiplike structure. It now appears worthwhile to consider designing a larger scale ship model to identify the behavior of that structure experimentally for comparison with the predictions from the data obtained during this small scale model program. It is suggested, therefore, that effort be devoted to the generation of such a design together with a suitable test program for the larger scale model, with the aim of procuring and testing the model in a project to follow the proposed next year of small scale studies.

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1. Becker, H., R. Goldman and J. Pozerycki, "Compressive Strength of Ship Hull Girders." NAS Report SSC-217, Part I, Unstiffened Plates, 1970.

2. Vasta, J., "Ultimate and Critical Compressive Strength of Tee Stiffeners." Experimental Model Basin Report 445, February, 1938.

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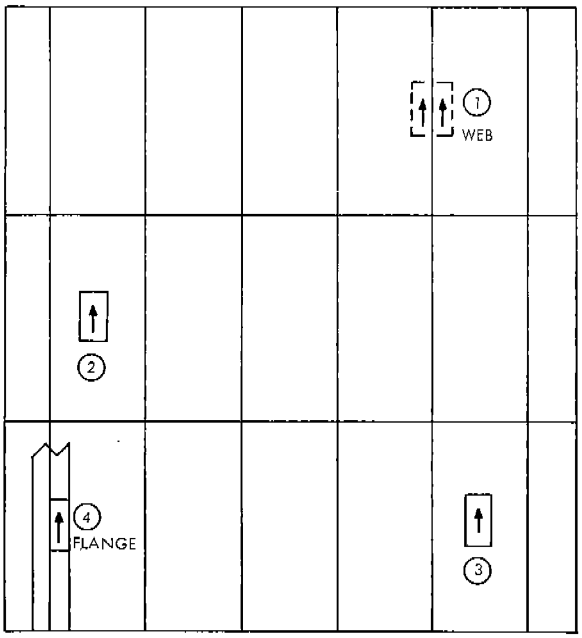
APPENDIX

STRAIN GAGE DATA

The primary purpose of the strain gage data acquisition was to obtain a check on the internal distributions of stress from the externally applied forces. The Poisson ratio strains for biaxial loading were examined as load increments were applied, and the bending stresses from the external pressure also were checked. In all cases the acquisition of strain data stopped well before failure was observed.

The sketches in Figures A-1 through A-5 depict the strain gage locations. Strains are summarized in Tables A1 through A5.



Strain Gages: EA 0.06 - 125 BIT
120 Micro-Measurements
All Back-to-Back on
All Grillages

Fig. A-1 - Specimen 4, Strain Gage Locations

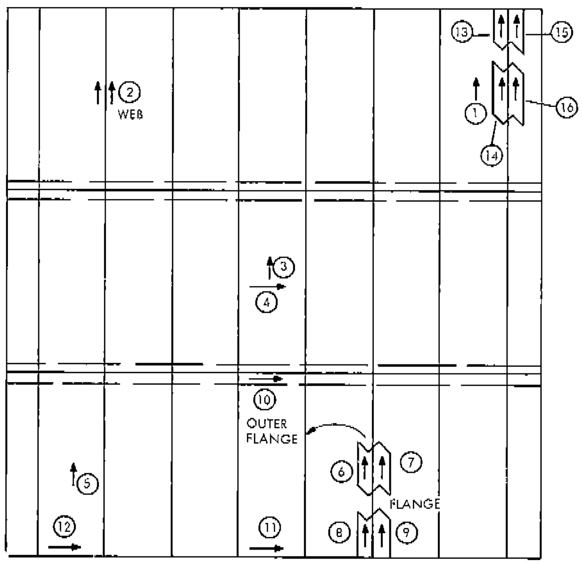


Fig. A-2 - Specimen 5, Strain Gage Locations

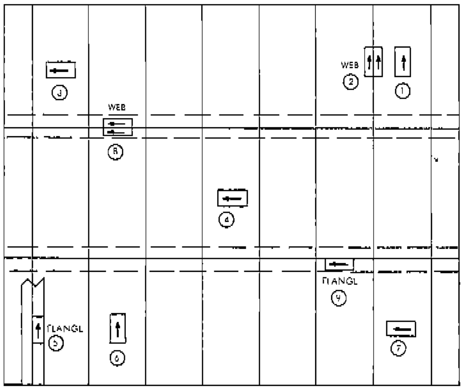


Fig. A-3 - Specimen 6, Strain Gage Locations

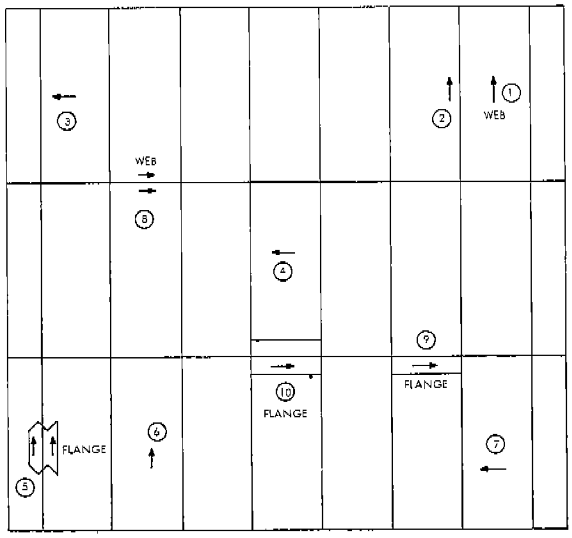
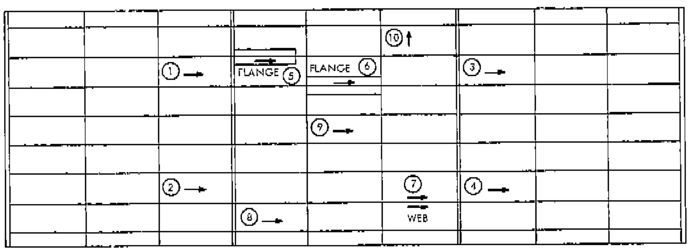


Fig. A-4 - Specimen 7, Strain Gage Locations



Bottom View

Fig. A-5 - Specimen 8, Strain Gage Locations

Table A1 - Specimen #4, Single Bay Grillage, N_x Loading and Strains

P_x (Lb.)	Strain μ Location				
	1	2	3	3	4
0	0	0	0	0	0
1,000	−75	−71		−76	−91
2,000	−150	−134		−134	−194
3,000	−224	−195		−180	−295
4,000	−300	−259		−244	−396
5,000	−374	−321		−298	−491
6,000	−448	−383		−352	−587
7,000	−522	−445		−401	−671
8,000	−599	−509		−455	−774
9,000	−679	−582		−515	−865
10,000	−758	−600		−583	−891
0	+49	−91		−20	+21
10,000	−697	−714		−584	−896
15,700		Failure			

Table A2 - Specimen #5, Single Bay Grillage, N_x, p Loading and Strains

P_x (lb.)	p (psi)	Strain μ Channel & Location 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	10.0	- 15	+ 40	- 80	- 22	- 42	+ 125	+ 127	- 5	- 15	+257	-28	+ 11	- 4	- 34	+ 19	+ 92
2,000	0	-8.4	-132	-119	+ 44	- 80	- 164	- 177	- 228	- 275	- 28	+ 6	- 09	- 25	- 9	- 16	- 48
4,000	0	-181	-258	-214	+ 73	-163	- 311	- 342	- 391	- 464	- 50	+ 23	- 10	-131	- 55	-102	-164
6,000	0	-266	-370	-310	+100	-248	- 461	- 496	- 510	- 593	- 73	+ 10	- 8	-285	-162	-266	-326
8,000	0	-330	-480	-418	+137	-328	- 605	- 640	- 613	- 701	- 94	+ 12	- 35	-362	-254	-384	-423
10,000	0	-416	-613	-526	+173	-418	- 733	- 800	- 730	- 822	-115	- 5	- 89	-448	-354	-495	-510
10,000	10.0	-420	-590	-612	+156	-453	- 618	- 675	- 745	- 820	+135	- 24	- 81	-445	-325	-467	-423
12,000	10.0	-516	-704	-714	+188	-540	- 745	- 787	- 880	- 930	+125	- 94	- 98	-558	-446	-587	-535
14,000	10.0	-623	-783*	-825	+220	-633	- 928	-1320*	-1234	-2085*	+104	-141	-129	-687	-590	-710	-649
16,000	10.0	-735	-821*	-946	+258	-743	-1170	*	-1660*	*	+ 90	- 58	-116	-866	-796	-876	-825

Ultimate Load 18,775 lbs.

*Drifting

Table A3 - Specimen #6, Single Bay Grillage N_x, N_y Loading and Strains

P_x (Lb)	P_y Load (Lbs.)	Strain μ Locations 1	2	3	4	5	6	7	8	9
0	0	0	0	0	0	0	0	0	0	0
000	0	- 29	- 40	+ 25	+ 8	- 110	- 47	+ 15	+ 7	0
2,000	0	- 70	- 95	+ 38	+ 21	- 188	- 95	+ 27	+ 12	- 7
4,000	0	-173	-210	+ 60	+ 44	- 335	-117	+ 55	+ 26	- 13
0	1000	+ 6	+ 1	- 47	- 57	+ 16	+ 10	- 56	- 53	- 43
0	1500	+ 15	+ 4	- 84	- 89	+ 20	+ 13	- 93	- 86	- 63
0	2000	+ 26	+ 13	-116	-116	+ 30	+ 21	-130	-110	- 77
0	2500	+ 36	+ 16	-153	-148	+ 31	+ 27	-164	-139	- 97
0	3000	+ 48	+ 26	-188	-176	+ 41	+ 35	-195	-164	-110
1,000	3000	+ 23	- 10	-159	-160	- 45	- 11	-172	-160	-115
2,000	3000	- 16	- 52	-140	-145	- 115	- 55	-155	-153	-120
4,000	3000	-107	-165	-109	-117	- 247	-140	-122	-140	-145
8,000	3000	-291	-386	- 51	- 60	- 507	-326	- 64	-126	-204
10,000	3000	-382	-498	- 24	- 30	- 760	-436	- 34	-120	-235
12,000	3000	-485	-615	0	0	- 911	-567	+ 2	-115	-273
13,000	3000	-535	-682	+ 11	+ 18	-1825*	-624	+ 5	-107	-300
14,000	3000	-593	-745	+ 27	+ 44	-2230*	-71.5	+ 37	-105	-330
15,000	3000	-645	-800	+ 46	+ 70	[illegible]	-784	+ 47	-100	-355
16,000	3000	-708	-862	+ 65	+ 94	[illegible]	-882	+ 25	- 75	-405
17,000	3000	-790	-681	+ 85	+131	*	-625	+ 45	- 66	-440

Failure Load 18,125 lbs.

*Drifting

Table A4 - Specimen #7, Single Bay Grillage Loading and Strains N_x, N_y, p

P_x (Lb.)	P_y (Lb.)	p (psi)	Strain μ Location 1	2	3	4	5	6	7	8	9	10
0	0	0	0	0	0	0	0	0	0	0	0	0
0	500	0	+ 8	+ 4	- 49	- 25	+ 24	+ 8	- 30	- 20	-14	0
0	1000	0	+ 11	+ 9	- 90	- 57	+ 45	+ 21	- 62	- 40	-23	+ 6
0	1500	0	+ 14	+ 14	-131	- 84	+ 65	+ 33	- 92	- 59	-35	+ 8
0	2000	0	+ 15	+ 15	-183	-116	+ 73	+ 39	-130	- 81	-45	+ 11
0	2500	0	+ 21	+ 21	-224	-140	+ 95	+ 46	-162	-104	-62	+ 11
0	3000	0	+ 28	+ 30	-241	-165	+ 113	+ 65	-186	-111	-63	+ 26
1,000	3000	0	- 3	- 10	-227	-136	+ 84	+ 74	-173	- 92	-60	+ 4
2,000	3000	0	- 54	- 66	-215	-116	+ 40	- 30	-160	- 80	-59	- 10
4 000	3000	0	-151	-170	-184	- 79	- 55	-116	-145	- 60	-60	- 50
8,000	3000	0	-355	-376	-113	- 5	- 273	-305	-101	- 02	-50	-101
10,000	3000	0	-464	-425	- 79	+ 35	- 417	-415	- 66	+ 20	-50	-140
10,000	3000	10.0	-469	-382	- 95	- 18	- 439	-441	- 65	+ 11	-60	+217
12,000	3000	10.0	-579	-325	- 49	+ 17	- 575	-540	- 29	+ 40	+55	+210
13,000	3000	10.0	-633	-334	- 30	+ 35	- 669	-600	- 13	+ 56	+59	+197
14,000	3000	10.0	-689	-342	+ 15	+ 35	- 745	-653	+ 6	+ 65	+65	+185
15,000	3000	10.0	-751	-313	+ 45	+ 78	-1510	-714	+ 27	+ 72	+72	+174
16,000	3000	10.0	-574	-326	+ 16	+ 86	-2076	-779	- 5	+ 70	+68	+152

Table A5 - Specimen #8, 3 Bay Grillage, Machine Loading and Strains

Machine Load (Lb)	Strain μ Locations 1	2	3	4	5	6	7	8	9	10
250	0	0	0	0	0	0	0	0	0	0
2,000	- 91	-126	-113	-150	-155	-145	- 97	- 139	-140	+ 18
4,000	-200	-274	-245	-323	-330	-315	-214	- 297	-306	+ 43
6,000	-309	-429	-380	-502	-509	-481	-330	- 455	-474	+ 73
8,000	-421	-592	-513	-694	-688	-646	-446	- 610	-638	+111
8,500	-443	-629	-532	-684	-731	-681	-467	- 650	-670	+118
9,000	-475	-669	-576	-644	-790	-734	-507	- 701	-716	+136
9,500	-509	-715	-618	-646	-709	-793	-544	- 756	-768	+150
10,000	-549	-760	-715	-654	-719	-830	-575	- 802	-815	+168
10,500 a	-588	-804	-769	-669	-759	-885	-605	- 740	-855	+187
11,000	-618	-843	-807	-681	-785	-956	-633	-1030	-910	+204
11,500 b	-648	-885	-865	-718	-788	-625	-681	-1280	-925	+223
12,000	-704	-928	-896	-715	-816	-646	-707	-1336	-940	+242
250	- 25	- 2	-121	+328	+274	+360	- 36	- 570	+ 60	+ 15

a Observable Plate Buckling

b End Panels of End Bays Fully Buckled

Ultimate Load 12,700 lbs.

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13. ABSTRACT

This is Part II of a two-part report on a year of investigation into the compressive strength of ship hull girders. This part covers stiffened mild steel plates with a/b = 3 and b/t = 50. Seven tests were conducted on panels and grillages loaded in axial compression in various combinations with transverse membrane compression and normal pressure. In addition, a three-bay girder was tested in pure bending.

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	ROLE	WT	ROLE	WT	ROLE	WT
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Compressive Strength						
Bi-axial Strength						

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