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THE BRITTLE FAILURE OF MEDIUM STEEL IN SHIP STRUCTURES

by

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PERSONNEL

Recent failures in welded merchant vessels, apparently brittle in nature, have given rise to extended discussion within the staff of the David Taylor Model Basin and with representatives of other agencies. The thought at the Taylor Model Basin on one phase of this subject is summarized here by Captain W.P. Roop, USN.

THE BRITTLE FAILURE OF MEDIUM STEEL IN SHIP STRUCTURES

ABSTRACT

Causes contributory to recent failures of ship structure, called "brittle," are discussed. It is pointed out that no single cause of such failures can be named, and that an increase of strength may be obtained in a variety of ways. Improvement should be made in those ways which will cause least interference with production.

INTRODUCTION

In the early days of sailing ships every owner carried his own insurance; the hazards of the seafaring life were lumped with other risks, and sea casualties were classed with famine and pestilence as necessary evils. So long as ships were small and their ownership and command were frequently merged in the same person, every motive existed for a satisfactory compromise between profit and security. Shipbuilding was a craft, guided much less by calculation than by skilled experience recorded mainly in the minds of the craftsmen. Merchant ships and war ships were not highly differentiated.

In the course of time a number of parallel developments occurred; the ships grew in size and the crews in numbers, the conditions of ownership changed, and the lines of competition, whether in war or trade, were more sharply drawn. Steam replaced sail as motive power. The name of Plimsoll became famous, the classification societies appeared. In the design of war vessels calculation became necessary in ever-increasing refinement. The adaptation of ship construction to the requirements of safe operation was improved and the risks of the sea were reduced.

Now in the midst of a world crisis risks have again risen. This is only partly a matter of direct enemy action; there is also an indirect but nevertheless very real effect on construction standards arising from the greatly extended use of welding and the urgencies of large-scale accelerated production.

The recourse, as in the earlier days of the classification societies, lies in a close study of casualties, but with the benefit of greatly improved techniques. Very thorough examination and analysis are being given to the vessels that have failed in service and to failures that have occurred in preparation for service, and careful inquiries are made into circumstances of load, design, quality of material, and workmanship. Brittleness and "locked-up stress" are among the questions raised in the present situation, which concerns welded ship structures almost exclusively.

The adverse effect of brittleness in ship steel has long been recognized, so much so that the necessity for specifying and meeting minimum requirements for ductility is considered of equal importance with ultimate tensile strength. However, since the advent of welded construction, a habit has arisen of ascribing structural failures to locked-up stresses, even though the elongations needed to relieve the residual stresses encountered can be shown to make up only a small fraction of the total elongation developed by a tensile test specimen.

There is in wide circulation a completely false idea which attributes to locked-up stress the power to cause rupture. The fact is that if a residual tension, say of 25,000 pounds per square inch, exists locally in a structure built of medium steel which has a yield strength of 40,000 pounds per square inch, then failure could *not* be caused by an external load which superposes a stress of 15,000 pounds per square inch on the residual stress under no load, even though the local stress would reach the yield point and local plastic strain would occur. What happens is rather that such an external load causes a plastic readjustment in the region around the point of high residual stress, and this results in a certain degree of "stress relief." This will always occur if the effect is local; the overstressing operation on the local area results in increasing the volume of the region subject to residual stress and reducing the intensity of that stress.

Unfortunately, the stress relief so obtained is not an unmixed blessing; something is lost; there is encroachment on what may be called the margin of ductility. The metal which has been subjected to plastic flow is nearer failure than before the stress relief occurred. The structure will withstand no less load than before, but its capacity for plastic deformation is reduced. In a word, it has become more brittle; it is now in the position of the man who still has considerable cash in the bank but who has drawn checks which lower the balance on his stubs and obligate the funds on deposit.

Brittleness, however, can arise from a variety of causes. It is common to attribute it to a quality of the material itself, and it is certain that materials do differ with respect to inherent brittleness. Even medium steel, though passed under current standard specifications, is far from being uniform in this respect, as the metallurgists have frequently pointed out. Perennial reproaches against the steel makers on this score may be heard in every shipyard.

The onus of brittle failure can be placed on the steel makers only in part, perhaps only in small part, because low elongation in the failures of assembled steel structures may certainly proceed from other sources. Some of these will now be briefly discussed.

EFFECT OF RATE OF LOADING

Even in what is called a static load, some time elapses during which the load is built up to its steady value. For dynamic loads in which the elastic limit or yield strength of the material is not exceeded, the effect of increasing the rate of application of the load is clearly understood (1)(2);* the matter is less clear when plastic flow occurs. There is the example of materials like glass, or steel at steam temperatures, which flow by creep under sustained load but give less plastic response to a blow. However, a reproduction of this phenomenon for medium steel at ordinary temperatures has not yet been proved.

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* Numbers in parentheses indicate references on page 10 of this report.

The yield strength of medium steel in general rises with the speed of the blow (3) but it is a fact, observed anew by Duwez and his associates (4), that under certain conditions the *energy* absorbed by a tensile specimen of medium steel diminishes with an increase in the speed of loading beyond a critical value. Nevertheless, it is not sufficient just to say that a high rate of loading induces brittle failure. In model and full-scale ship structures which are loaded by underwater explosion at a very high speed, there is no evidence that the rate of loading alone causes brittleness. On the contrary in the tests summarized in Reference (3), on tensile specimens of usual form the energy absorbed up to rupture shows a moderate increase as the rate of loading increases. Since it is the product of load and elongation that determines energy absorption, increase in plastic stress must be sufficient to offset loss of elongation if the energy value is to be maintained. Observation shows that the increase in stress exceeds this necessary amount.

These comments apply to very high rates of loading, but it is quite possible that a similar situation exists at lower speeds if other circumstances favor brittleness. Such a circumstance may be low temperature.

EFFECT OF TEMPERATURE

Medium steel definitely loses ductility at low temperature. This effect is to be distinguished from the effects of low temperature in the process of making, fabricating, and assembling the steel; reference is made here rather to the temperature at which the steel is loaded, either in a test or in service.

The loss of ductility at low temperature has been studied by Henry (5) by impact tests, where it appeared as a reduction of the energy absorbed before rupture. In a more recent report by Holloman and Zener (6), the loss of ductility appears in the form of a higher stress needed at lower temperature to produce a given plastic strain. They found a close correlation between temperature and speed effects which permits rather exact prediction of one by observation of the other.

EFFECT OF NOTCHES

Elastic stress concentrations caused by notches have become familiar through photoelastic studies, and they offer an easy explanation for failures at low values of average stress. This explanation, however, does not suffice for some anomalous facts. Thus endurance specimens fail in fatigue below their yield strength even though stress raisers are thoroughly eliminated. Various materials differ strongly with respect to the effects produced by notches, that is, in "notch-sensitivity." In particular, the effect of a notch on the behavior of materials beyond their elastic limits is still obscure. In some materials a notch will form the origin of a tear which by a process of progressive failure produces a rupture with little elongation; the material is therefore called brittle. In other materials a notch may "wash out" and appear as little more than a scar on the surface after extended plastic flow has occurred.

Medium steel has intermediate properties with respect to the effect of notches. In the presence of a notch, necking begins at a lower average stress than it would without the notch. The extent of the necking is limited by the acuity of the notch and the consequent restriction of the field of stress concentration. Elongation in the specimen or the element is therefore localized. From the point of view of energy absorption the structure as a whole appears to be brittle even though the energy absorption per pound of metal at the apex of the neck may have a high value. At the same time, if the crack originating in a region of stress concentration can be led to a region of lower general intensity and terminated in a crack stopper, like the round holes sometimes deliberately drilled for the purpose, then the reduction of notch effect may be enough to save the situation.

This subject is now being studied, and motion pictures of the progress of a crack during the process of failure are available (7).

EFFECT OF STRAIN HARDENING

Cold working of medium steel is considered to be deleterious; it is for this reason that excessive drifting, and raising of the yield point by cold rolling and similar practices are forbidden. Any increase in the yield strength at the cost of ductility is also undesirable because it likewise leads to brittle fracture.

These familiar facts are cited to support the idea that a design procedure which puts the permissible working stress in a fixed ratio to the yield strength ignores the part played by the metal beyond the yield point. The use of ultimate strength and a larger safety factor is preferable in this respect, at least for tensile failures. However, there is another point of view from which the plastic action of the metal can be regarded, which leads to more valid considerations.

Instead of the increase in stress in the strain-hardening range, it is the plastic deformation which should be emphasized. Any spread between ultimate and yield *stress* is of no value unless it goes with a spread between ultimate and yield *deformation*. In a word, it is the capacity for plastic *energy* that counts, when the margin of safety in a structure is being considered.

The truth of this proposition depends on the nature of the load which a ship experiences. In long, shallow vessels operating in the still water of rivers and the like, the static loads predominate, so that the design of the vessel resembles that of a building or bridge; even slight permanent deformation is not acceptable because if the actual stress exceeds the yield strength over any considerable extent of metal, there is risk of collapse. In these circumstances deformation will not in any case cause relief of the load, and may increase it, with catastrophic results. Only the strain-hardening factor saves the situation.

On the other hand, most ship structures have to meet loads at once dynamic in nature, uncertain in intensity, and sporadic in occurrence. It is not at all true that failure will always follow if the stress at any point exceeds a given value, or even if it exceeds the "ultimate" value as determined in a static test of a specimen.

Consideration must certainly be given to the duration and the recurrence of the load; in other words, to impact and fatigue.

It is the belief at the Taylor Model Basin that the rupture of metal in ship structures can be accounted for in terms of the energy involved in plastic flow. It is certain that the yield strength as the sole criterion of failure in ship structures is inappropriate. Ships, and especially parts of ships, can stand considerable local deformations without loss of the whole vessel. The passage of the yield point marks the beginning of the critical useful service of a piece of steel, not its end. The service which it can perform depends far more on the amount of plastic deformation it can withstand than upon the stress at which plastic flow begins, or even than the rise of plastic stress through strain-hardening.

When the yield strength has been artificially raised, as by cold-forming, proof-testing, auto-frettage, or similar processes, the capacity of the metal for resisting static load without permanent deformation has been raised but its reserve of capacity for absorbing energy by plastic deformation has been reduced. Its margin of ductility has been encroached upon and it is therefore that much nearer to what will be regarded, when it happens, as a brittle fracture.

EFFECT OF BIAXIAL STRAIN

In the standard tensile test, longitudinal elongation is accompanied by transverse contraction. In the elastic range the amount of this contraction is indicated by Poisson's ratio, which varies with samples of metal. In the plastic range, however, the contractile strain in each of the two transverse dimensions is half the tensile strain in the direction of the load; this arises from the fact that plastic changes in volume are negligible compared with changes in form, as shown in Figure 1.

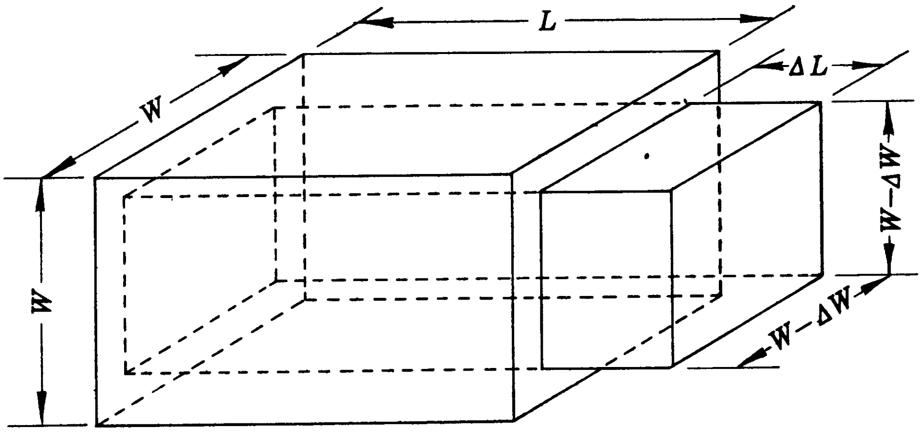

Figure 1 - Diagram Illustrating Changes in Shape Due to Plastic Flow

Transverse contraction compensates for the increase in length by plastic flow so that the volume is unchanged.

$$\frac{\Delta L}{L} = -2\frac{\Delta W}{W}, \text{ since } LW^2 = (L + \Delta L)\ (W - \Delta W)^2$$

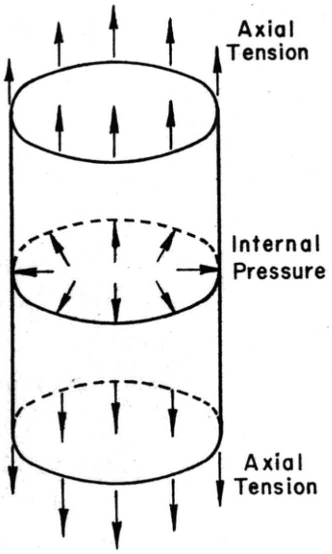

Figure 2 - Tube under Combined Axial Tension and Internal Pressure

The internal pressure causes a hoop stress which is transverse to the axial stress.

These relations are clarified by tests in which transverse load is applied in addition to the longitudinal load, as in a tubular specimen under combined axial tension and internal pressure; see Figure 2. The internal pressure increases the diameter and decreases the length, and, when the internal pressure is combined in a fixed ratio with axial tension, the longitudinal elongation is less than it would be if the internal pressure were not present. In the presence of a sufficient transverse load, the longitudinal contraction will exceed the elongation caused by the direct load; the application of a longitudinal load thus seemingly results in a negative longitudinal elongation. This occurs when the hoop stress exceeds double the longitudinal stress. It happens that this limiting condition is obtained by closing the ends of the tube and applying internal pressure alone without *external* axial load.

Failure under these conditions will occur by formation of an axial split in the wall of the tube. Such a case is shown in Figure 3; the measured axial elongation is actually near zero, and the pressure causes an increase in diameter at midlength of the tube, which leads to failure by a longitudinal split.

When the transverse stress is less than the axial stress, it is to be expected that fracture will occur in a transverse section. When the transverse stress is small enough this undoubtedly occurs.

However, when the two stress components are nearly equal, it is not entirely clear as to the mode in which failure will occur. In the example shown in Figure 4, the axial stress at failure was 1.4 times the hoop stress. Rupture occurred in the transverse section, as would be expected, after an elongation of over 20 per cent. However, the internal pressure was enough to prevent any necking in diameter so that the break has the appearance of a brittle fracture.

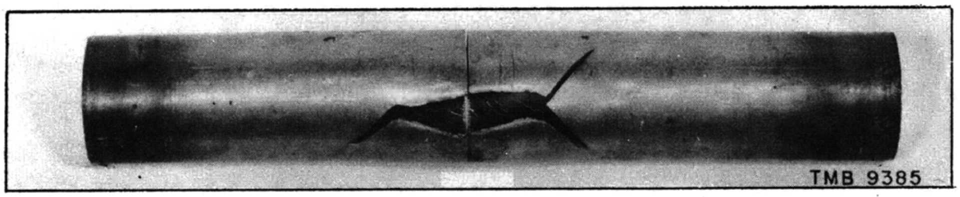

Figure 3 - Failure by Axial Split under the Action of Hoop Stress

The straight transverse saw cut was made after the break under test load.

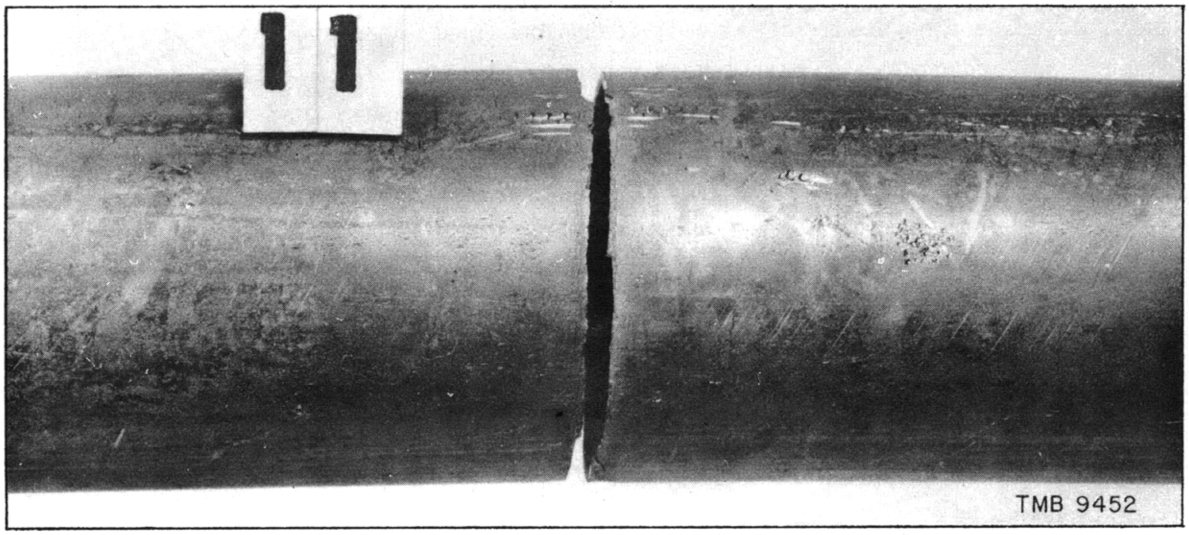

Figure 4 - Failure in a Transverse Section under Axial Tension

Failure was caused by axial stress superposed on a constant hoop stress.

As the circumstances of this test may have affected the result, the following details are given. A sustained internal pressure of 5000 pounds per square inch was applied to a tube closed at the ends; the pressure at which the tube would fail by splitting is 7000 pounds per square inch. This pressure when applied alone produced a slight increase in diameter but no observable change in length. Axial tension was then applied, in addition to that due to the internal pressure acting on the ends. At a combined tension nearly the same as that at which rupture occurred in pure tension, the transverse fracture occurred, as shown in Figure 4.

Although a cursory examination of both these cases would indicate that the failures were brittle they would, on closer study, be found ductile, notwithstanding that in both cases the change in tube diameter was small.

Even in the case where the longitudinal elongation was zero, and where the hoop stress was double the axial value, the failure could not truly be called brittle, in view of the local loss of thickness. Apparent absence of elongation alone is therefore not an adequate criterion of brittleness.

COMMENTS ON ENERGY ABSORPTION

"Brittle" means easily broken or fragile; when steel is examined after fracture it is called brittle if there is little evidence of plastic flow near the break; in particular, if there is little necking, elongation, and reduction of area. Even when these are present, if they are extremely localized the break may still look like a brittle one.

These ideas may be given more exact expression in terms of the energy absorbed in the process of rupture as a measure of ductility.

When a transverse load is combined with the axial load on a tensile specimen, the axial elongation is reduced; if the combined loads are carried to failure, a superficial indication of brittleness appears. However, if ductility is judged by absorption of energy instead of elongation alone, it is seen that the failure is not brittle. It may be that, for lack of strain, the axial load does no work, and the loss of thickness involves no energy for lack of a radial component of stress; even in such a case, the transverse load would do work and the failure would therefore be considered not brittle.

BRITTLE FAILURE IN SERVICE

Except for tensile failures due to stress concentration and fatigue at holes and notches, the normal mode of failure of a ship structure when overloaded in bending is by buckling in the compression flange of the girder (8). For some years attention has been given mainly to attaining a degree of reinforcement against failure by instability which would assure that the metal could be worked to its yield strength without buckling.

Recently, however, failures have occurred which suggest that a new emphasis on the behavior of ship steel in tension is needed. At the time of writing, the cause of these failures is the subject of extensive inquiry in which the Taylor Model Basin has had a minor part.

"Brittleness" is a word that continually recurs in any discussion of this subject. The purpose of the foregoing is to show that the term "brittleness," as ordinarily used, does not denote a property of the metal alone, but that brittle failure, as observed in the recent tensile failures mentioned, is affected by all of the circumstances which have been described.

Thus strain-hardening may well have been a decisive factor in the situation even though the strain values which have been observed in pertinent tests are relatively small. It is a fault of the technique of observation that it is never possible to obtain a true value of strain at a point but only an average value taken on a finite base length. A strain of 1 or 2 per cent may be all that shows on a base length of 10 inches but if the strain is concentrated, the local value over a base of say 0.1 inch may go right up to 25 or 30 per cent and so cause local initiation of failure.

Notch sensitivity, though not excessive in medium steel, is nevertheless present and this material is therefore unable to overcome the bad effects of concentration of stress and strain caused by the presence of unavoidable notches.

Temperature effects, though not pronounced, were present in those failures which occurred in cold weather. It is unfortunate that the critical temperatures of medium steel fall within the range of ordinary atmospheric variations.

Rate of loading appears in no case to have been very high; nevertheless loads that were not completely static in nature actually occurred. When other conditions are adverse it may be that only a slight increase in rate of loading is needed to finish the job.

REMEDY FOR OBSERVED FAILURES

It seems certain, at this stage of the investigation, that no single cause for the failures can be named. Various adventitious causes have been suggested, such as hasty welding, lenient inspection, faulty material, untried designs intended to expedite construction, temperature stresses, and the residual effects of improper welding sequences. It is almost certain that no one of these is accountable, and it is naturally a controversial question how far any one may be present in any given case.

On the other hand, as it was a combination of adverse circumstances that caused failures, it is also true that a combination of improvements in practice can prevent them. Although the search for a single specific reason for the failures is almost sure to be in vain, there is an equivalence, with respect to the various features of practice mentioned, such that stringent application of some of the requirements of good practice, especially those that do not unduly retard production, may be sufficient. Perhaps these precautions may be enough to make up for the unavoidable encroachment on good practice that the emergency requires.

There is thus posed the question: What adverse practices are unavoidable and which can be remedied so as to reduce the risk of failure? We will not make the mistake of saying that all adverse practices must cease, because the emergency demands risks that would not be permissible in peace time. At the same time it would be equally wrong to say that nothing must be allowed to interfere with production, since ships that cannot carry out their missions are useless, and, as shown by recent incidents, the present risk of structural failure is certainly too high.

At the time of writing the answer to this question is not to be found by calculation, nor even by experiment and laboratory or field tests alone; the situation calls for action on the production front. This must be conducted in a way that bears some resemblance to action on the fighting front, by reconnaissance in force to find spots where advantage can be taken, either by relaxing unnecessary requirements in order to speed production, or by tightening necessary requirements by the minimum amount which will reduce the risk of structural casualty to a satisfactory degree.

Relaxation seems already to have gone too far. The remedy therefore is to seek improvement of present practice to bring it as far as possible into accord with pre-war standards. Naturally those measures which will yield the greatest return, such as more rigorous inspection of welding workmanship, will receive the greatest emphasis. It is hoped that in this way it may be found unnecessary to alter too radically the time-saving features of the designs involved.

It is necessary to find a way to judge the prospects of success for measures which may be proposed. Numerous inspections and tests have been made by various agencies for the purpose of identifying the cause of failures and providing suggestions as to appropriate remedies; these have included extensive observations of strain distributions under known loads. Reduction, study, and interpretation of the data obtained are necessary. In particular the vibration test on the SS SHILOH and the static deflection test on the SS BELLE ISLE await a thorough study for which there has not yet been time. The tests on welding procedure at the University of California are also expected to contribute to the solution of the problem. Observation and discussion of the presence of plastic action in these interpretations has received strong emphasis, and experimental work intended to improve general understanding of plastic action has been taken in hand. Also an extensive experimental program has been launched which looks well beyond the practical measures which must be taken immediately.

In the meantime the present memorandum is offered as a summary of the opinions at the Taylor Model Basin on this problem.

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