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W. A. P. Fisher, B.A., A.M.I.Mech.E.
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W. A. P. FISHER, B.A., A.M.I.Mech.E.

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Summary.—The effect of clamping on the fatigue strength of joints in aluminium alloy is investigated experimentally. Tests on Z-section stringers connected to long, slotted cleats give an endurance for tightly clamped joints about nine times that for unclamped joints. Tests of bolted joints in aluminium alloy sheet material show still greater improvement for very tight clamping. In both series of tests, the clamping tends to cancel the weakness in fatigue of a loaded hole.

Tight clamping is considered to have many applications in design of aircraft joints from the standpoint of fatigue strength.

1. *Introduction.*—The majority of aircraft joints intended for transmitting tensile load are formed by connecting at least two members by bolts, pins, or rivets carrying shear. It is well known that stress concentrations are produced at the boundaries of the holes through which these pass. In fatigue tests of such joints, failure of one or other member usually occurs through the end holes, owing to the peak stress being higher there than elsewhere.

Hitherto, the stress concentration at such holes has been regarded as depending on the geometry of the hole and the associated part, and in a minor degree on the fit of the bolt in the hole. Consequently, in attempts to obtain the best fatigue strength for a joint of a given type, attention has been concentrated on designing the joint so as to reduce the proportion of load carried by the end bolts.

Evidence that failure does not invariably occur at a bolt hole, however, was recently obtained from a test on a Z-stringer joint under 1*g* mean load. This joint had nine bolts in double shear on the axis of the Z-section, connecting it to a slotted cleat. In five tests out of six, the initial fatigue crack occurred in the plain section of stringer immediately under the end of the cleat, and *not* through a bolt hole. From the appearance of the web surface in the region of the fracture, it was concluded that fretting was the primary cause of failure under these conditions.

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* R.A.E. Report Structures 121, received 16th May, 1952.

These results were provisionally explained by the clamping effect of the tightened bolts, and accordingly it was decided to make comparative tests on two specimens of the joint in question, with one as received from the aircraft manufacturers, and the other with the nuts loosened. The tests showed that the endurance of the loosened joint was only 11·3 per cent of that for the normally assembled joint. This evidence is supported by results from a separate series of tests on the effect of tight clamping in single-bolt joints in aluminium alloy sheet.

2. *Tests on Z-stringer Specimens.*—Six stringer-joint specimens and their fractures are shown in Figs. 1 and 2. With the exception of specimen No. 6, in which a cleat failure occurred, the fatigue failure originated in the stringer web just inside of the end of the cleat.

In all 6 specimens, the transverse bolts joining the cleat to the stringer were of light alloy, excepting the extreme outer and inner bolts, which were of steel.

In order, from either end, the sizes of the bolts were:

Bolt No.	1	2	3	4	5	6	7	8	9
Size	2 B.A.	$\frac{1}{4}$ in.	$\frac{5}{16}$ in.	$\frac{3}{8}$ in.	$\frac{3}{8}$ in.	$\frac{3}{8}$ in.	$\frac{5}{16}$ in.	$\frac{1}{4}$ in.	2 B.A.
Material	Steel	——— aluminium alloy ———							Steel

This arrangement of sizes is considered a favourable one for good load distribution between the bolts. In addition, it will be noted that the cleats are uniformly tapered.

The endurances at a 1g mean load of 2·34 tons are shown in Fig. 3. It will be noticed that all the points lie fairly close to the mean curve, showing that the scatter is not great, despite the fact that the failures originated by fretting. These joints satisfied the Royal Aircraft Establishment criterion of fatigue strength for aircraft structures and joints, which is defined as follows:

> 'When fatigue-tested at 1g mean load and an alternating load of 7·5 per cent of the ultimate design load the specimen should withstand not less than 2 million cycles before failure.'

Two further specimens were tested in order to investigate the influence on endurance of

(*a*) stiffness of the transverse bolts,

(*b*) friction due to clamping between the stringer and the cleat.

In both specimens, steel bolts replaced the light alloy bolts, and the specimens were tested at the same mean load as the six previous specimens. They were both subjected to an alternating load of ±0·78 tons, at which two of the previous six specimens had been tested. The two additional specimens are identified as follows:

Specimen A — Nuts tight (as received)
Specimen B — Nuts slackened off to avoid clamping.

The machine used was the 20-ton Avery Schenck fatigue-testing machine.

2.1. *Test Results.*—*Specimen A* failed by rupture of the stringer from a transverse fatigue crack just inside the nose of the cleat (Fig. 4a).

Endurance 1·214 *million cycles*. *See* point A in Fig. 3.

Note: Endurance and mode of failure both agree with results from previous specimens.

Specimen B failed by rupture of the stringer *through the bolt hole* nearest the point of entry of stringer web into the cleat (Fig. 4b).

Endurance 0·1375 *million cycles*. *See* point B in Fig. 3.

Note: Change in position of failure, and reduction of endurance in the ratio 1/8·85.

2.2. *Discussion of Results.*—*Specimen A.* Evidently the change from light alloy bolts to steel ones had no noticeable effect on the endurance.

Specimen B. Considering the good agreement between the original tests, the great reduction in endurance shown by specimen B is far beyond the limits of scatter. The transfer of the point of failure to the first bolt hole shows that, in the absence of clamping, the stress concentration at this hole must be more severe than when the nuts are tight.

It cannot be supposed that the friction can relieve the bolts completely of fluctuating shear load ; at the same time, these results demonstrate that, in a suitable type of joint, the clamping obtainable in normal practice can prevent failure through the bolt hole. In so doing, the clamping can in favourable circumstances, raise the endurance in a ratio approaching 10 to 1.

3. *Tests on Double-shear Single-bolt Joints.*—Confirmation of the beneficial effect of tight clamping on the fatigue strength is provided by the results of tests on double-shear joints using a single bolt.

3.1. *Description of Specimens.*—The specimens consisted of a central 1-in. wide strip of 16 S.W.G. aluminium alloy sheet between two 20 S.W.G. strips, connected by a 2 B.A. mild steel bolt. To avoid other possible effects on the fatigue strength of these joints arising from variation of bolt fit, an easy push fit was maintained on all specimens, thus isolating the factor to be investigated, namely the effect of clamping. Details of these specimens are shown in Fig. 5.

The specimens tested in the clamped condition were fitted with three standard 2 B.A. mild steel washers under both bolt head and nut to spread the pressure over the full area covered by the washers ; the bolts were tightened with a normal spanner until yielding was felt. On the unclamped specimens the nut was positioned on the bolt to prevent possible spreading of the specimen, but no pressure was applied.

3.2. *Test Results.*—The endurance curves obtained from clamped and unclamped specimens are shown on Fig. 6.

The fatigue strength of the clamped specimens is vastly superior. The following analysis indicates the degree of improvement.

	Clamped (a)	Unclamped (b)	Ratio (a/b)
Endurance for 400 lb alternating load	800,000	25,000	32/1
,, ,, 300 lb ,, ,,	4,000,000	45,000	89/1
,, ,, 200 lb ,, ,,	10,000,000 (unbroken)	150,000	?

or, alternatively:

Alternating load for 10,000,000 cycles	280 lb	60 lb	4·65/1
,, ,, ,, 1,000,000 ,,	380 lb	100 lb	3·8 /1
,, ,, ,, 100,000 ,,	700 lb	230 lb	3·05/1

The mean load was 650 lb in all tests.

Static strength of 2 B.A. mild steel bolt in double shear: 3,000 lb approx.
Tensile strength of 16 S.W.G. central piece through hole: 4,000 lb approx.

3.3. *The Effect of Clamping on Mode of Failure.*—Fig. 7 illustrates an unclamped specimen failure, two clamped specimen failures and a clamped specimen prior to testing. The unclamped specimens invariably fractured at the hole, whilst the line of fracture on the clamped specimens was generally clear of the hole and approximately coincident with the edge of the washers.

3.4. *Clamping and Friction Measurements.*—The extent of clamping was approximately determined by testing bolts in tension, these being found to yield in the threaded portion at 1400 lb load. Hence the clamping pressure exerted by the single bolts in the test specimens was probably within the range of 1300 lb to 1500 lb.

Static tests on clamped specimens were then done, using a sensitive extensometer as a means for indicating slip. In these tests, the hole in the centre strip was slightly elongated by filing, to enable the incidence of slipping to be readily determined. By this means, the average tensile load which could be carried by friction was found to be 450 lb.

4. *Discussion.*—The above test results from a relatively complex form of stringer joint and from a simple form of double-shear joint clearly illustrate the fundamental influence of clamping on fatigue strength and on the mode of failure.

That substantial gain in fatigue strength can be obtained in thin members without excessive clamping is indicated by the fact that the stringer joints showing this advantage were assembled by the manufacturers in a normal manner.

The explanation of why the fatigue strength of the stringer joints is so greatly improved by the clamping effect of the bolts is simple. The connection, being effected partly by friction, takes place over a considerable area, instead of at a series of isolated holes. In effect the two members behave as though cemented together, except that there is a small relative movement where the stringer enters the cleat ; hence the stress distribution is more uniform than when the load is transferred entirely at the bolt holes. If the specimen behaved as a single piece of material, the most effective stress concentration would be at the sudden change of cross-section where the cleat begins, *i.e.*, where the failure did in fact occur. The incomplete adhesion at this section presumably relieves this stress concentration, but introduces a certain amount of fretting which eventually gives rise to a fatigue failure.

When the clamping is such that failure occurs in one member at the end of an overlapping member, instead of through a bolt hole, it is to be assumed that no extra benefit would be obtained by greater tightness of clamping.

4.1. *Effect of Low Temperature.*—The coefficient of thermal expansion of aluminium alloy is about twice that of steel. When a joint of aluminium alloy members has steel bolts under considerable tension at normal ground temperature, there must be a loss of tension at ambient temperature of (say) —50 deg C. The clamping friction will be correspondingly reduced, with adverse effects on the fatigue strength. This is not the case, however, when the bolts are also of aluminium alloy. In aircraft which normally fly at high altitudes there is, therefore, some advantage in designing for the use of aluminium alloy clamping bolts rather than steel ones, or in using a steel with as high a coefficient of expansion as aluminium alloy, *e.g.*, D.T.D. 247.

4.2. *Types of Joint in which Effective Friction is Obtainable.*—The form of member most favourable for exploiting the benefits of high clamping is one which is thin compared with its width. In joining such members, a considerable number of bolts are required for utilising the strength of the full cross-sectional area ; hence the total clamping force, and therefore the friction, is higher than for thick members. In addition, thin members, because of their lateral flexibility, require very little initial tightening to obtain firm contact. Most wing stringers, for example extruded Z-sections, are in this category. As already seen, these can be clamped effectively if a long slotted cleat is employed. Double-scarf joints with a long taper should also be amenable to tight clamping. In U-shaped stringers, where the connecting bolts extend across the U, effective clamping can be obtained by the use of tight-fitting spacers inside the U and surrounding the clamping bolts.

With regard to riveted joints, the present tests indicate that tightness of riveting and a high coefficient of friction would be beneficial in fatigue. Although, in the case of aluminium alloy riveting, there is not the shrinkage effect which is present in hot-riveted steel structures, it can be demonstrated that tight riveting can introduce considerable clamping friction.

4.3. *Implications in Regard to the Fatigue-Testing of Joints.*—It is clear that, when a number of similar joints are tested in fatigue, differences in the amount of tightening can give a wide scatter, although under static test these differences would not show up.

In assessing the fatigue strength of an aircraft joint by the testing of specimen joints, the tightness of the clamping bolts must be the same as in the aircraft otherwise the test specimen will not be representative. It is obvious, too, that when protective paints or jointing materials are used between the surfaces, these should be exactly reproduced in the test specimen, and should be properly set before the test is made. Instances have occurred where chromate jointing paste used in fatigue-test specimens was found to be still wet when the specimen was dismantled after test.

4.4. *Proposed Further Investigations.*—Although the basic principle of tight clamping for the improvement of fatigue strength is now definitely established, there are numerous aspects yet to be investigated.

Probably the first question to be determined by test is whether the fatigue strength improves progressively with clamping tightness, or whether there is a critical tightness at which there is a sudden increase in fatigue strength, corresponding, perhaps, to the change in the mode of failure. Further tests should be made to establish whether or not the benefit of tight clamping applies equally well to alternating loads of mixed amplitude as to loading at fixed amplitude. A further point which arises is the influence on fatigue strength of surface treatment and finish by their effect on friction and surface fretting.

All the joints used in the tests reported here were assembled dry. The use of sticky jointing material or chromate paint would probably have an adverse effect, but this question should be settled by tests. Cementing the joint, as with certain modern cold-setting materials, in addition to the use of transverse bolts, could be expected to give excellent fatigue strength. Suitable workshop methods for controlling the deliberate clamping of joints will have to be developed.

5. *Conclusions.*—Two distinct sets of fatigue-tests show that tight clamping can be a factor of major importance in the fatigue strength of joints. One type of specimen consisted of a connection between an extruded Z-stringer and a slotted cleat. The other was a double-shear joint in aluminium alloy sheet, clamped with a steel bolt. Tight clamping was found to increase the endurance by a factor of 9 in the first type, and by an even greater amount in the second. The increase in endurance is accompanied by a change in the mode of failure, such that the cracks originate at the boundary of the clamped area instead of at the bolt holes. The beneficial effect of clamping in the Z-stringer-cleat joint was obtained in the joints as normally assembled. It should be further noticed that in six of the Z-stringer joints the bolts were of light alloy except the end ones, which were of steel. The influence of clamping on fatigue strength will be felt most in joints of thin members, such as flat sheet, rolled sections and stringers.

Some of the implications of these results have been considered, in regard to both design and testing. Differences in clamping tightness could sometimes account for wide scatter in fatigue tests of nominally interchangeable specimens.

It is not claimed that the limited evidence in this report goes further than establishing the importance of the principle of clamping joints as a means for increasing fatigue strength. The scope and technique of application of this principle are subjects for further research.

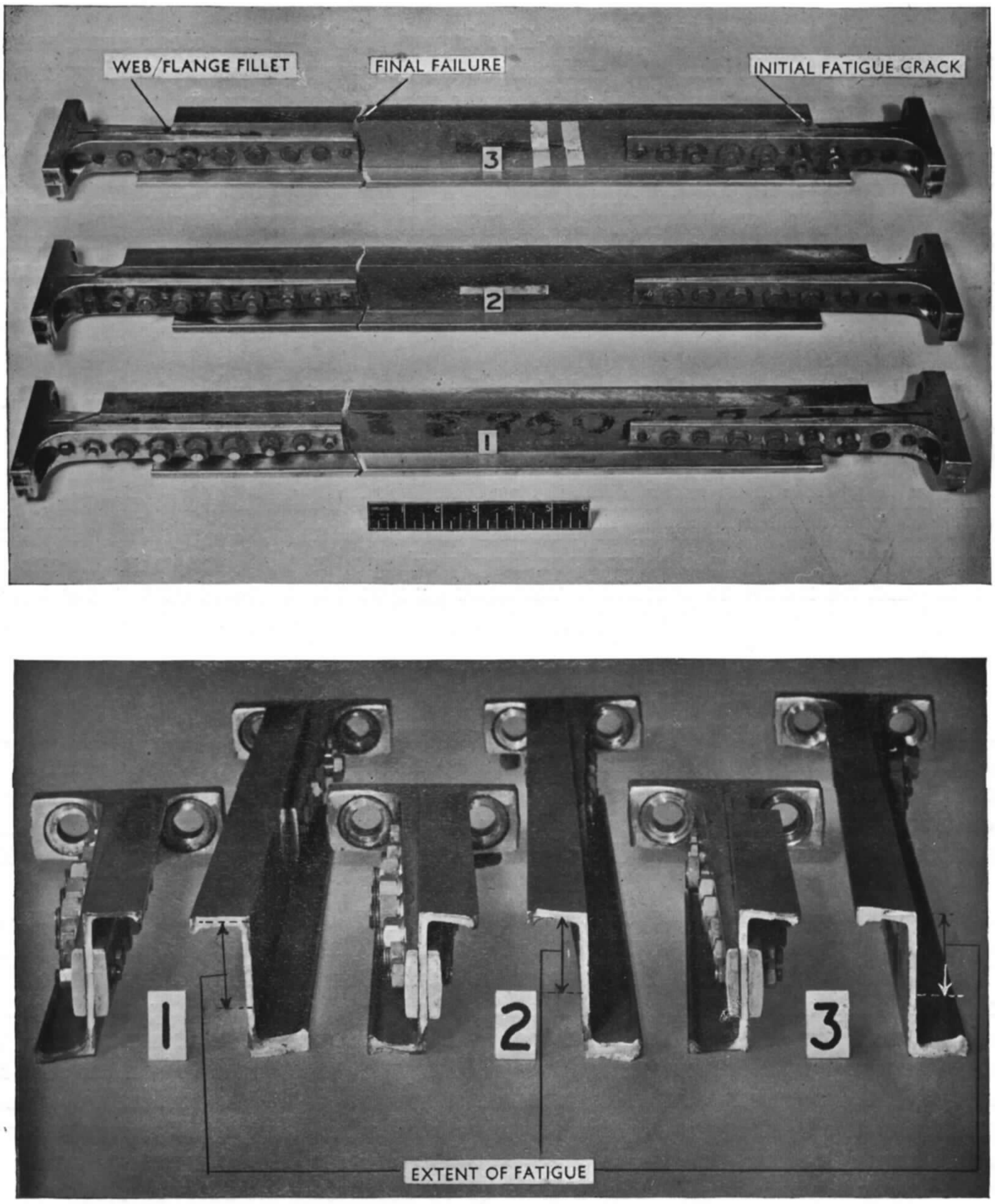

FIG. 1. Specimens after failure. Nos. 1–3.

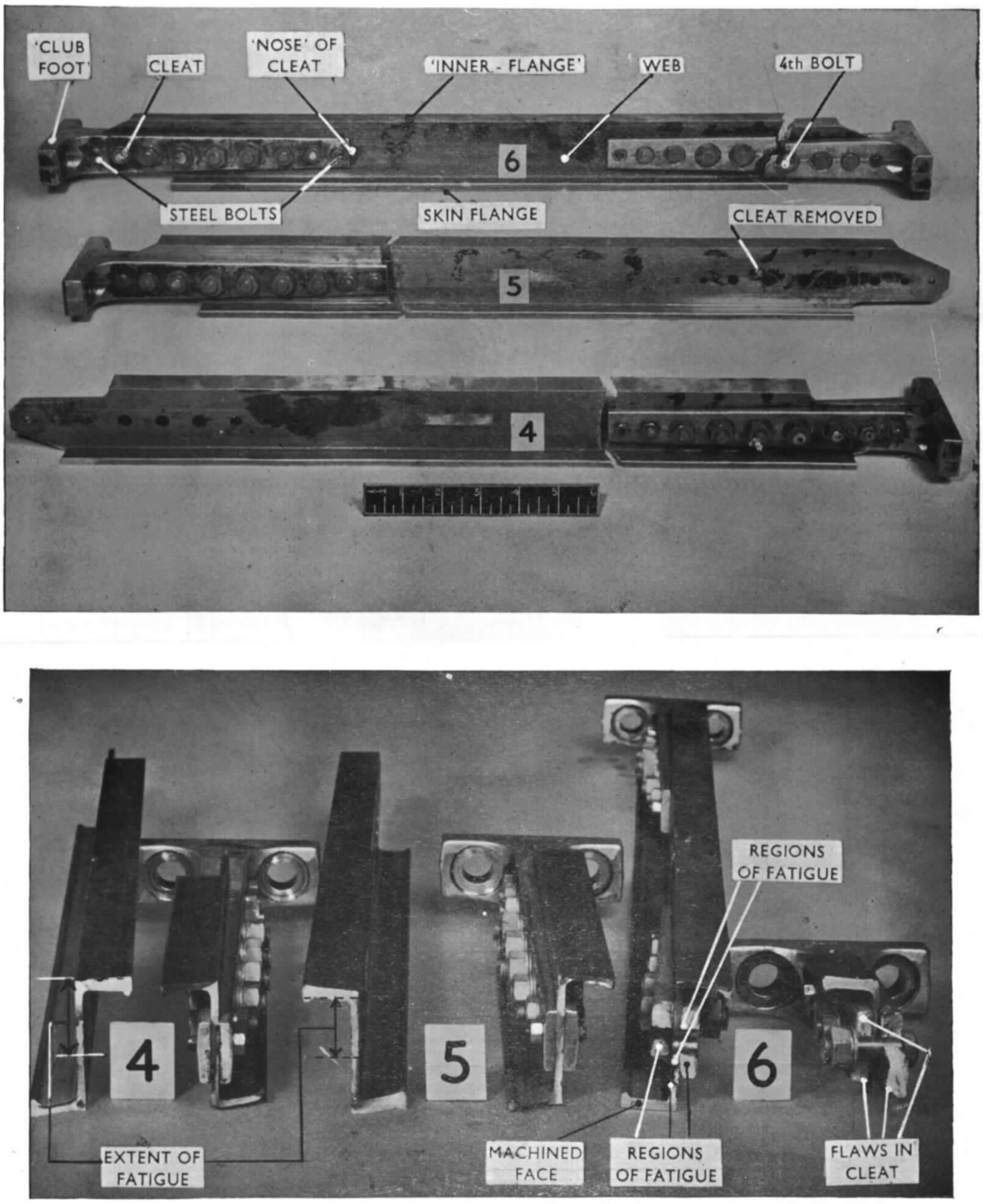

Fig. 2. Specimens after failure. Nos. 4–6.

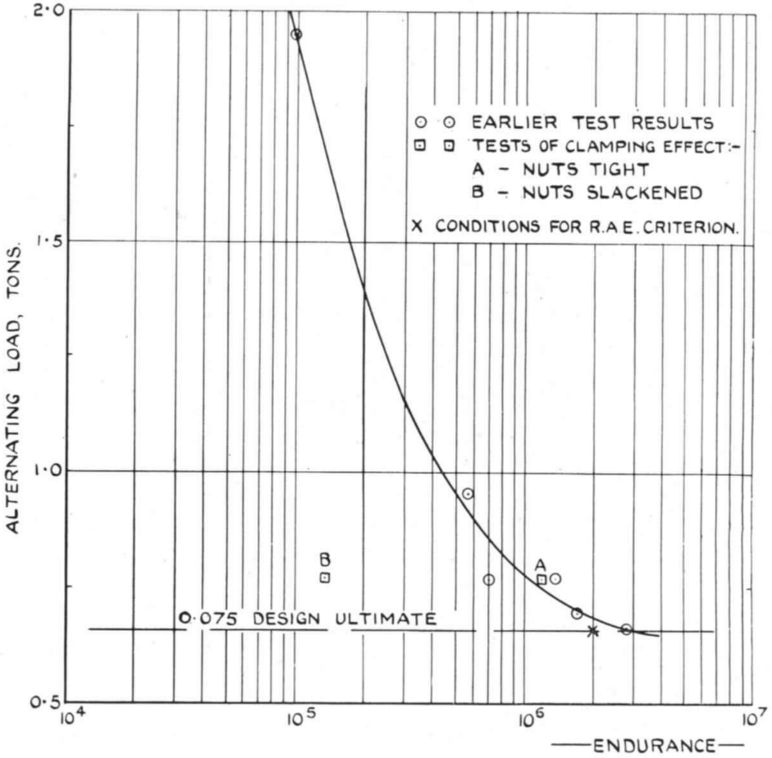

FIG. 3. Load-endurance curve for stringer joints at a 1g mean load of 2·34 tons.

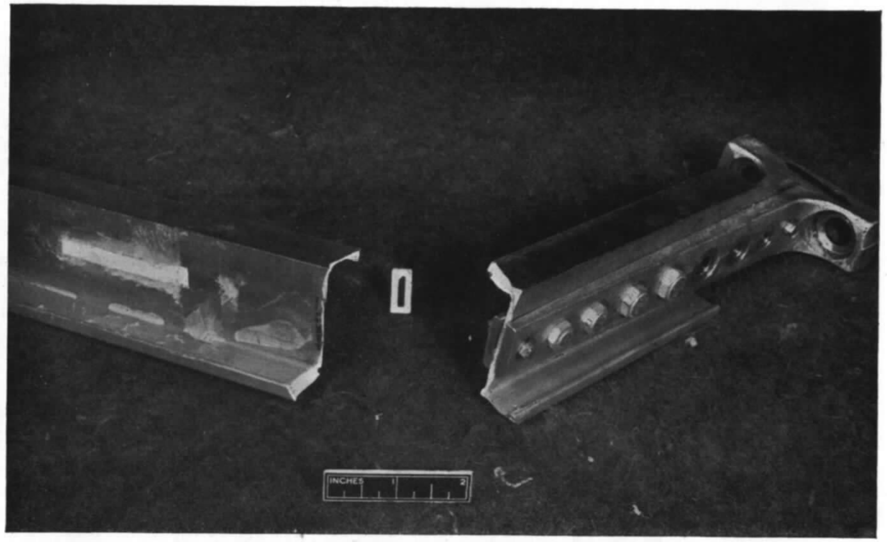

FIG. 4a. Nuts tight. Crack starts well clear of bolt hole.

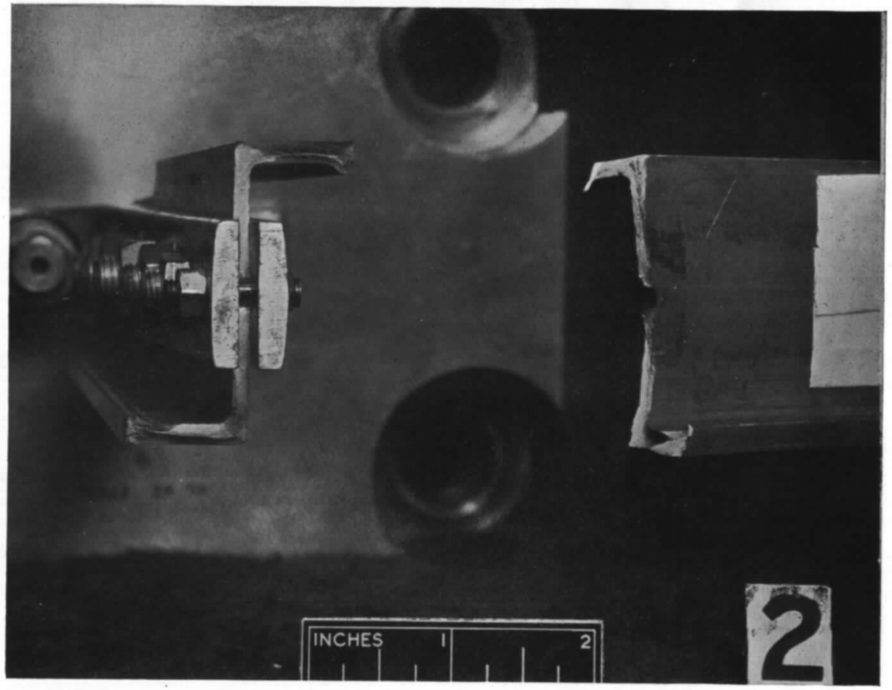

FIG. 4b. Nuts slackened. Crack starting at bolt hole.

FIG. 4. Effect of clamping on mode of failure.

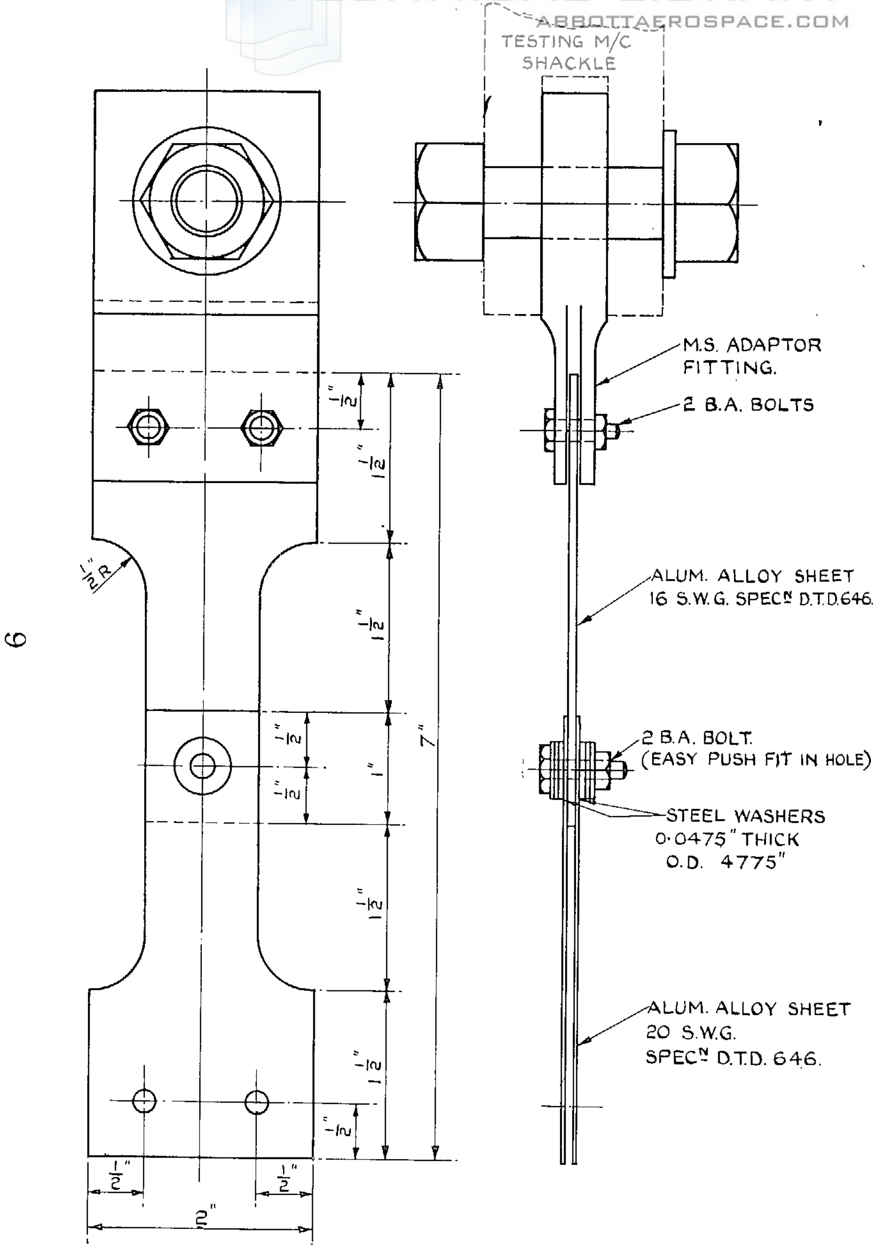

FIG. 5. Fatigue-test specimen (single-bolt—double shear).

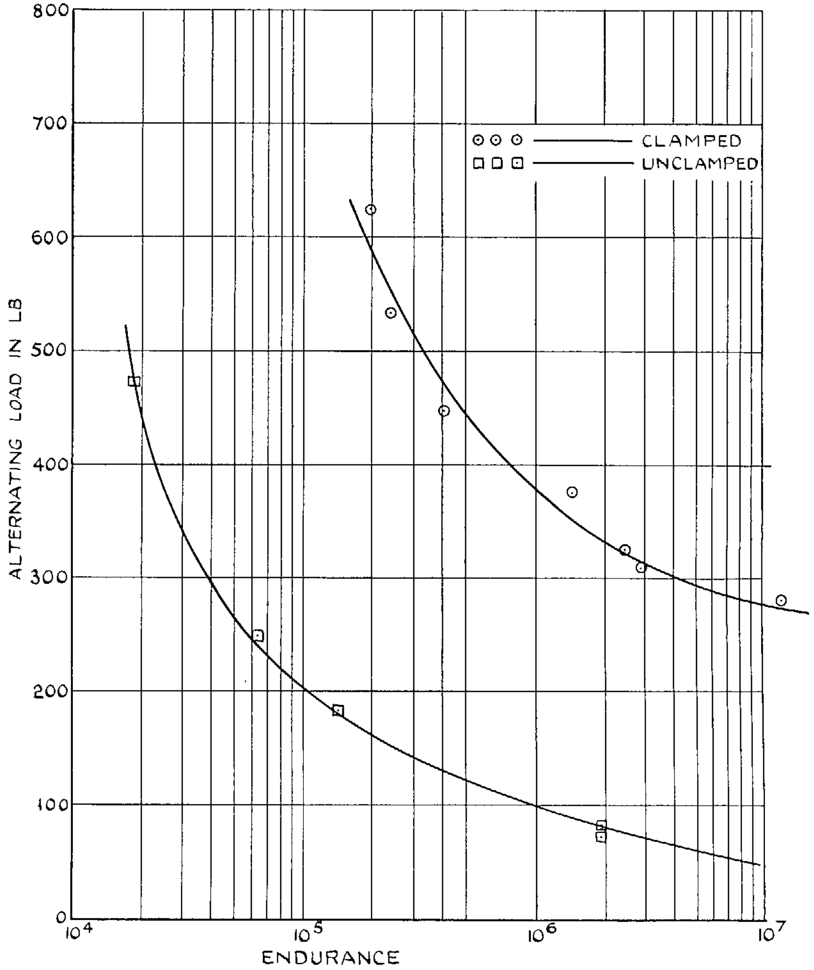

FIG. 6. Load-endurance curves for simple double-shear joints shewn in Fig. 5.

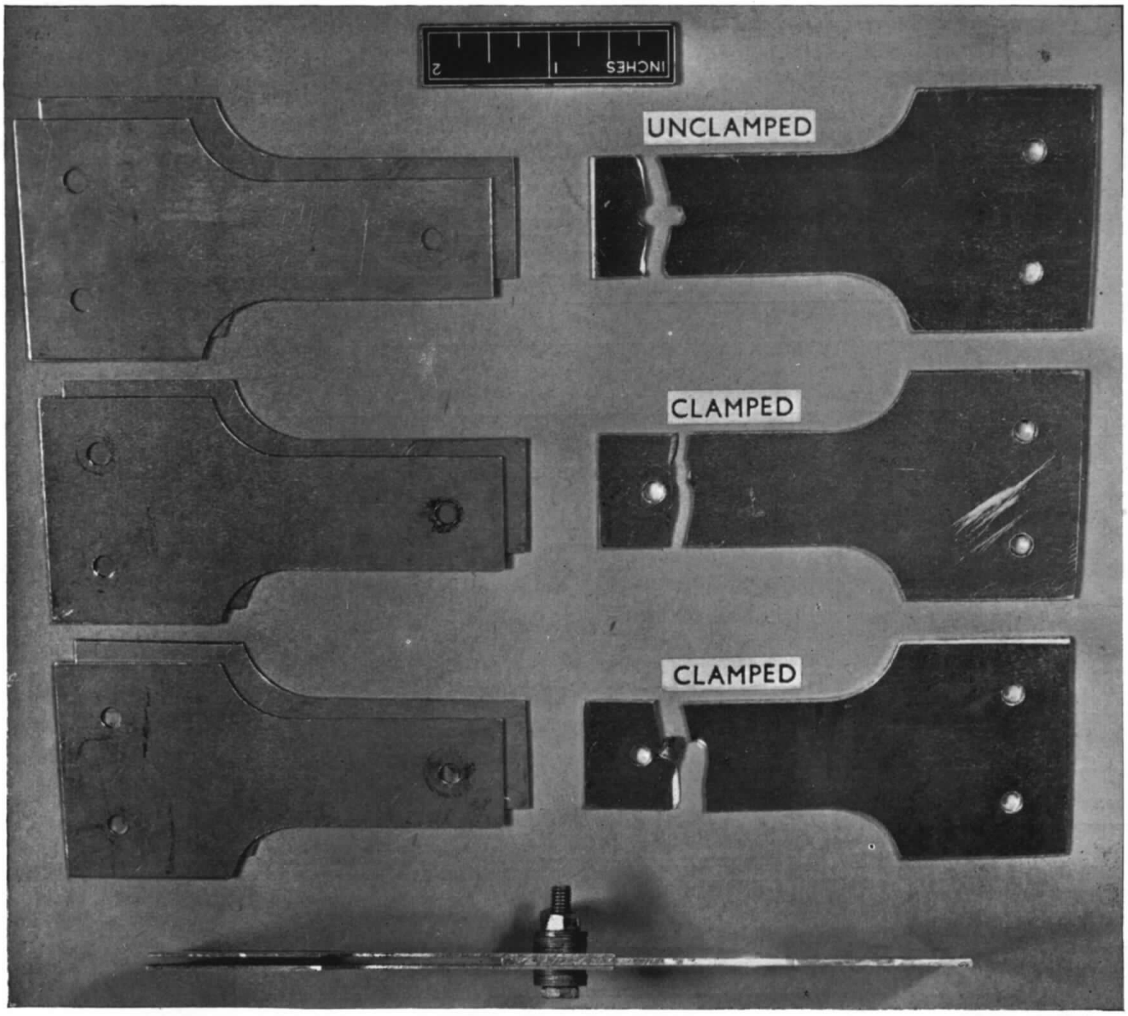

Fig. 7. Modes of failure of simple double-shear joints.

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