Slip Front Mechanisms in Mechanical Joints

CLARK T. ROLLINS* AND PAUL E. SANDORFF†
Lockheed-California Company, Burbank, Calif.

Photoelastic investigations were made of the stress environment occurring in the members and at the contact surfaces of clamped or bolted-clamped double lap joints. Slippage is observed to occur in such joints with the first application of load, the slippage initiating first at the extreme edges. The demarcation between slipped and unslipped regions, called a "slip front," moves lengthwise along the joint as load is increased; associated with it are unusual stress conditions and stress concentrations that were evaluated. The phenomenon is believed to be a primary cause of fretting in joints and therefore to be significant to fatigue strength.

Introduction

FRETTING fatigue has come to be recognized as an important, if not dominant factor in determining the fatigue life of aircraft structural joints. Basic to fretting and fretting fatigue is the transfer of at least a portion of the load through friction. Friction load transfer is important even after gross slippage has occurred, allowing the major part of the load to be carried by the fastener.

The investigation reported here originated as an exploratory study of the interrelationship between three important fretting parameters which would apply in structural joints; namely, normal pressure, tensile stress, and slip. A photoelastic model was devised to simulate a uniformly clamped double lap joint which transferred load entirely by friction. Test results with this model revealed that joint slip was progressive in nature, initiating at the edge of the joint at a very low value of joint axial load, and involving more of the joint surface as load was increased. This phenomenon, and the resulting complex stress distribution, has been termed a "slip front mechanism."

In actual joint structure, clamping is nonuniform. To investigate what effect this condition might have on joint slippage phenomena, a second photoelastic study was conducted on a double-lap joint model which simulated the nonuniform clamping introduced by a centrally located bolt.

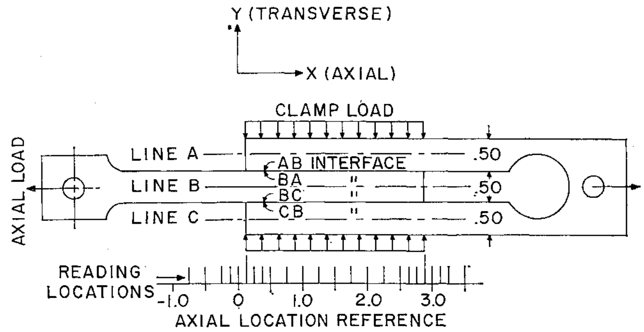

Fig. 1 Double lap joint model and reading locations.

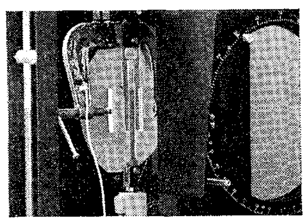

Fig. 2 Uniformly clamped model in the polariscope loading frame.

Method

Methods used in the preparation and treatment of photoelastic specimens, and in the analysis and reduction of data, were for the most part conventional and are well established in the literature.[1-4]

A sketch of the lap joint model in which uniform clamping was used is presented in Fig. 1. The model was mounted in a 12-in. field research polariscope, as shown in Fig. 2.

Photoelastic data on normal and oblique fringe values were obtained on the member centerlines (A, B, and C) under increments of clamping load, and then, with the clamping load held constant, under increments of axial load. On the interfaces the normal incidence fringe values and the principal stress directions were determined. Representative photographs of the specimen under load are presented as Fig. 3.

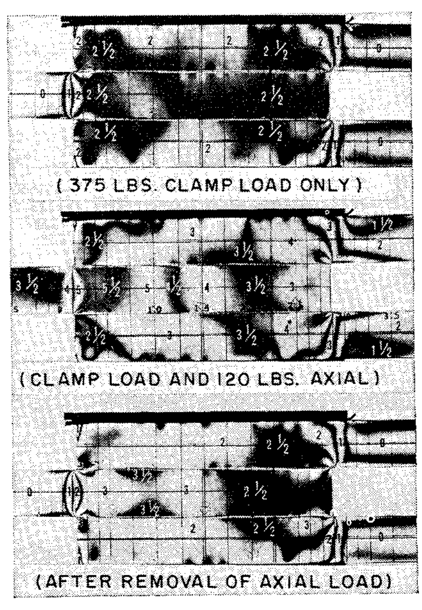

Fig. Fringe patterns in the model with various loading.

Received April 5, 1971; presented as Paper 71-370 at the AIAA/ASME 12th Structures, Structural Dynamics and Materials Conference, Anaheim, Calif., April 19–21, 1971; revision received May 11, 1972. This work was sponsored as part of a Lockheed funded Independent Development Program.

Index Category: Structural Static Analysis.

* Senior Research Engineer, Dynamics Group, Science and Engineering Branch.

† Senior Research and Development Engineer, Structures Division, Science and Engineering Branch. Associate Fellow AIAA.

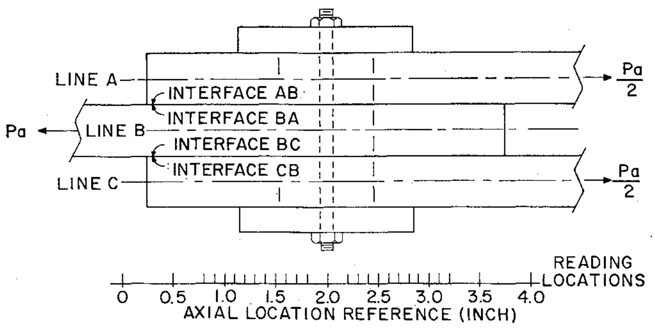

Fig. 4 Bolted double lap joint model and reading locations.

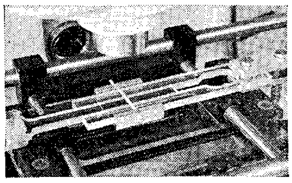

Fig. 5 Bolted model in the optical comparator polariscope.

The bolted lap joint model was designed to simulate a double lap configuration of 0.10 in. thick aluminum alloy sheet fastened with a row of No. 10 steel screws or bolts and 0.35-in. diam washers spaced 0.54 in. apart. An axial load of 42 lb and bolt load of 100 lb in the model corresponded to a prototype tensile stress of 10 ksi in the aluminum alloy sheet and bolt load of 1200 lb. The photoelastic model is shown schematically in Fig. 4. All dimensions in the plane of the model were a 5 × enlargement of the prototype, except for the bolt hole diameter, which was restricted to $\frac{1}{8}$-in. diam to assure sufficient strength of the $\frac{1}{4}$-in. thick plastic at the bolt hole location. A clamping bolt of 0.10 diam was used, which allowed sufficient clearance so that pick-up of shear load by the bolt could be avoided. The aluminum blocks, simulating the washers, were relieved in thickness on the inner surface out to the dimension of the true scale bolt hole in order that maximum compressive stress would occur at that location. The model mounted in the loading frame of the optical comparator polariscope is shown in Fig. 5.

Results of Tests on Uniformly Clamped Model

Normal Stresses

Transverse (clamping) stress σ_y and axial (tensile) stress σ_x on the joint member centerlines, calculated on the basis of normal incidence and oblique incidence fringe data, are shown in Figs. 6 and 7. These stresses are quite regular in nature and interaction between the two is seen to be small. For the qualitative purposes of the present study, the small interaction between σ_x and σ_y justified the assumption that the σ_y distribution at the interfaces remained unchanged throughout the experiment.

The axial stresses on interfaces *BC* and *CB* at, and after, each of several values of axial load are plotted in Figs. 8 and 9. In regions in which slip had not occurred, axial stresses on the interface were essentially uniform and proportional to axial load. At the location of the slip front, wide departures from this condition are noted—on the interface *BC*, the axial stress was abruptly increased, while the opposite effect

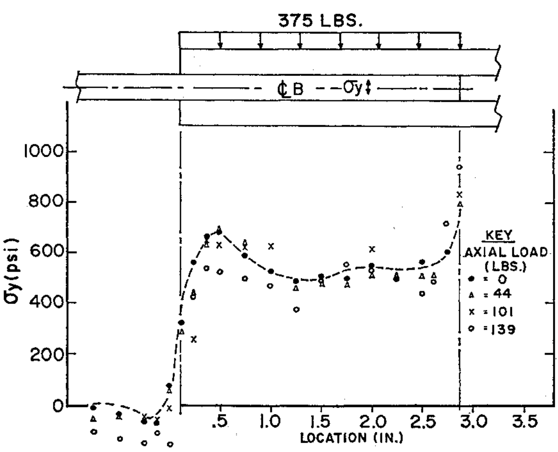

Fig. 6 Transverse stress (σ_y) along ℄B at various axial loads.

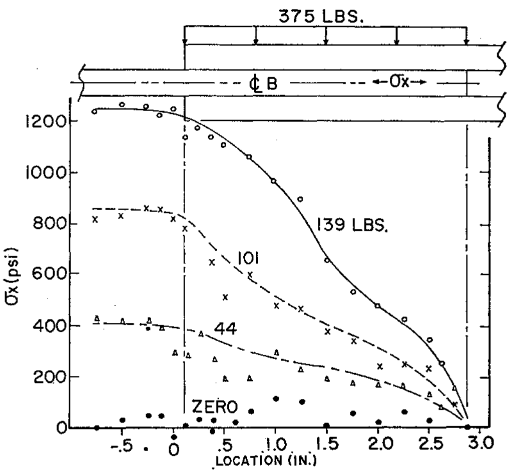

Fig. 7 Axial stress (σ_x) along ℄B at various axial loads.

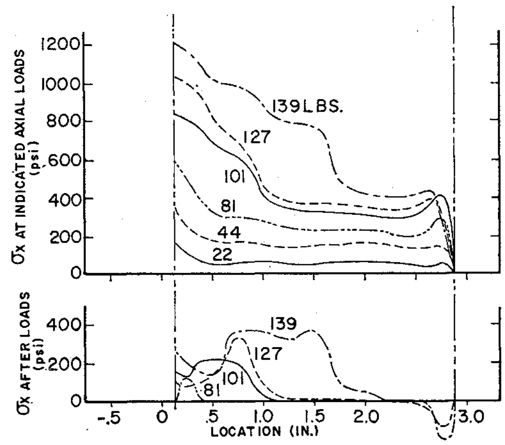

Fig. 8 Axial stress along interface *BC* at and after axial loads.

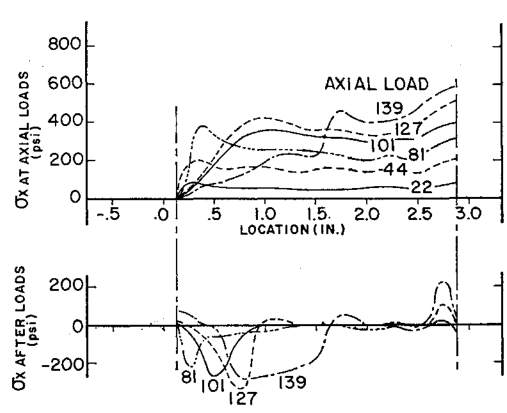

Fig. 9 Axial stress along interface *CB* at and after axial loads.

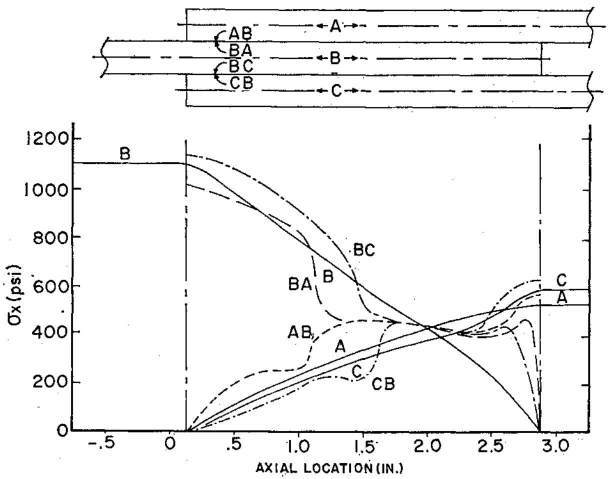

Fig. 10 Axial stress along all line and interface locations at 139 lb axial load.

occurred on the interface *CB*. These abrupt variations were matched by the pattern of residual stresses which remained when the axial load was removed. The location of the slip front is established by these disturbances in the stress distribution at the interface. As axial load was increased, it is seen that the slip front moved along the length of the joint. At higher values of axial load, slip had also initiated on the opposite end of the joint.

The axial stresses at all centerline and interface locations are plotted in Fig. 10 for the axial load of 139 lb. It is seen that the centerline stresses remain fairly regular over the entire length while the axial stresses at the interfaces reflect the local disturbance due to the slip front. In the unslipped region the stresses are compatible across the interface, while behind the slip front a discontinuity exists.

Shear Transfer across the Interfaces

The shear stresses (τ_{xy}) acting on the interfaces were determined from analysis of the data taken at normal incidence and the principal stress direction.

Clamping load-only caused some τ_{xy} stress on the ends, but left most of the interface unaffected. With application of axial load, the τ_{xy} stresses required for equilibrium developed primarily at the ends of the interface. When these shear stresses reached a critical value, slip occurred, resulting in reduced shear stress in the region of slippage and increased shear stress in the unslipped region. Fig. 11 is a plot of τ_{xy} along interface *AB* and *BA* with clamp load only, with 139-lb axial load, and with the axial load removed.

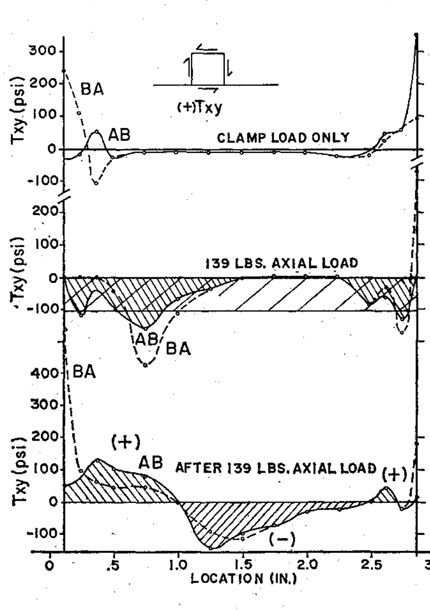

Fig. 11 τ_{xy} distribution on *AB* and *BA* at various loads.

Slip Front Mechanism

The plots of τ_{xy} indicate that the region of actual slippage lagged the bifurcation of axial stress by a significant distance. The incompatibility of axial strains, on opposite sides of the interface, which exists in the region transferring the highest shear stress, is believed to result from nonlinear deformations of asperities. These would be below the resolution of this experiment. The clamped lap joint which transfers shear by friction is therefore visualized as being comprised of the following:

1) The main part of the joint far ahead of the slip front, which behaves essentially as homogeneous material (that is, friction acts as a bonding agent).

2) The slip front itself, identified as a region which transfers shear effectively, but which undergoes unusually large relative shear displacement producing incompatibility of strains, as a result of deformation of asperities. The forward edge of this region is identified by the bifurcation of axial stresses on opposite sides of the interface.

3) The region immediately behind the slip front, in which gross relative motion (slippage) has occurred, with an associated reduction in shear transfer. The boundaries between the zones described above would not be clearly distinguished, since they reflect changes in the statistical distribution of microscopic processes.

Results of Tests on Bolted Model

The transverse (σ_y) stress along the horizontal centerline of the bolted model resulting from bolt clamping is shown in Fig. 12. Results are presented in terms of loads and stresses which would apply for the prototype aluminum alloy bolted joint. It is evident that clamping effects did not extend far beyond the region under the simulated washer, and that the interface area which would be involved in frictional load transfer did not vary greatly with the clamping load. The decrease in clamping stress adjacent to the bolt resulted from the shape of the simulated washer.

For the balance of the tests, bolt clamping load was held constant at 1200 lb. The effect of application and removal of axial load on shear transfer stress τ_{xy} at the interface is illustrated in Fig. 13. The shear stress distribution has

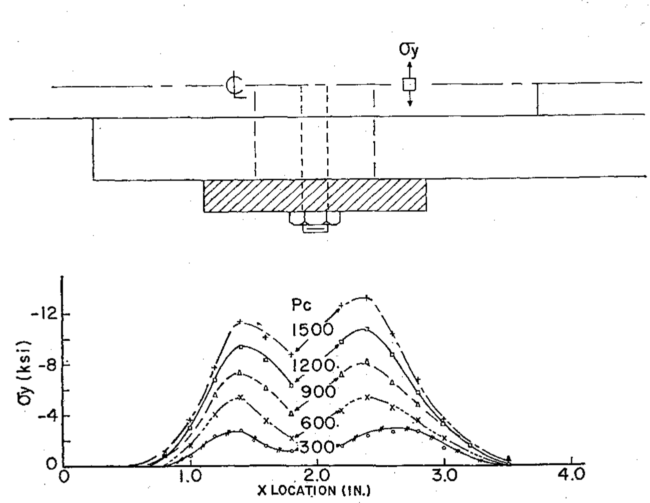

Fig. 12 Compressive prototype stress distribution along ℄ due to bolt load.

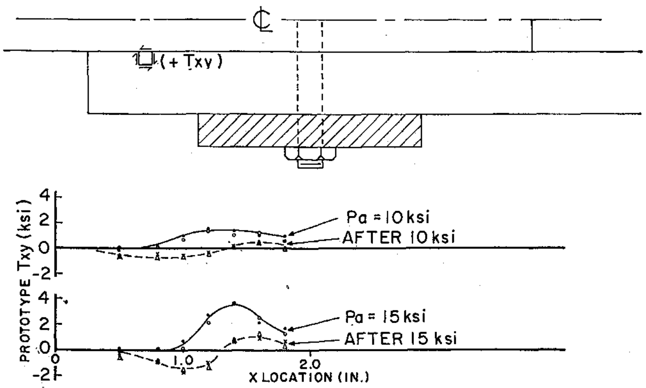

Fig. 13 Shear stress distribution along interfaces *BC* and *CB* at and after two axial loads.

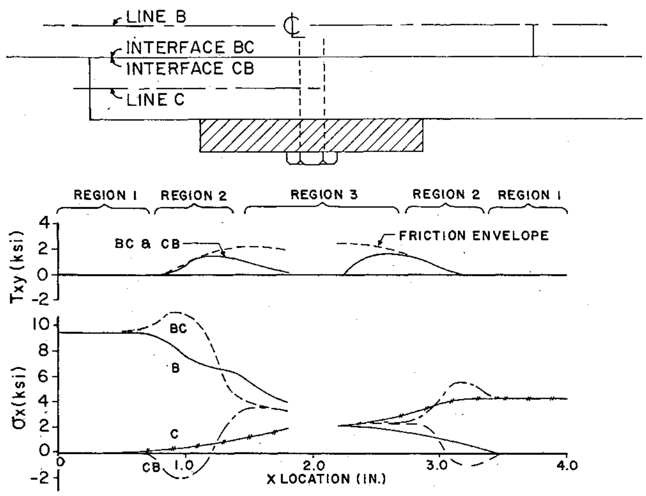

Fig. 14 Interrelationship of prototype stresses at 10 ksi skin stress.

approximately the same shape as the clamping stress distribution of Fig. 12, suggesting that limiting shear at any station is established by a coefficient of friction times the clamping stress.

Axial stress distributions along the joint member centerline and interfaces, together with the corresponding interface shear stresses, are presented for a representative loading condition in Fig. 14. When load is removed, the regions at which the stress concentrations occur are subjected to stresses of the opposite sign as a result of the residual stress condition noted previously. Under repeated load, therefore, these interface areas must suffer stress excursions appreciably different and larger than those at the member centerlines.

Three different regions are identified in Fig. 14. In the first region, members may overlap but act independently since very little or no compressive clamping stress is acting. In the second region, transverse compression exists, consequently frictional shear transfer occurs. Axial stresses and axial displacements differ on opposite sides of the interface; however, the existence of shear transfer produces rapid changes which bring about compatibility in the third region. Here, continuity of all stresses and displacements is maintained across the interface.

Conclusions

Slippage Mechanism

As load is first applied to a joint operating in friction, a strong stress concentration occurs at the very end of the region of contact. When the load is increased, shear transfer stress in these critical end-regions exceeds that which can be carried in friction, and local slippage occurs. This region of slippage expands with further increase in load, and it is possible to chart the progress of the slip front along the joint interface as a function of the applied load.

Ahead of the slip front the two joint members behave as though bonded together, whereas behind the slip front, they are displaced substantially in shear. The front itself is of finite width and is characterized by high shear transfer, as well as by shear displacement across the interface ranging from zero up to the break-away value. This behavior probably involves plastic yielding of asperities. In this way the slip front provides a practical resolution of the discontinuity which would otherwise exist in the local stress field.

Fretting in Riveted and Bolted Joints

In the ordinary mechanically fastened lap joint, an annular region about each rivet or bolt is subject to a clamping pressure, and this pressure varies in magnitude, falling to zero at the outer edge of the annulus. This distribution is the opposite of what would be desired to best resist the shear transfer under friction. In fact, since frictional shear transfer initially must peak at the extremes of the contact area, where clamping stress goes to zero, it appears that a slip front must be established here even under infinitesimal loads.

Under repeated load, fretting is frequently observed to occur in such an annular area on the interfaces. Conditions which promote fretting may include the stress concentrations associated with the slip front and the residual stress patterns induced under repeated load as well as the microscopic interactions at the interface.

Friction Grip Design

In laboratory testing of fatigue specimens, loads are often introduced by means of clamping devices or grips utilizing only friction. If the slip front mechanism applies in this case, the jaws of such grips should be quite short in length in order to use clamping force most effectively. This principle has been put into practice with considerable success.

Wear and Fretting of Mechanical Systems

Conditions leading to wear, fretting, and fretting fatigue in mechanical systems and machinery, often involve surfaces of considerable extent bearing against each other. In such cases, the slip front mechanism appears as a possible mode of slippage, as opposed to the elementary concept of relative motion being uniform over the entire length of the contact area. The literature on wear and fretting is remarkable for the inconsistency in reported results and disagreement in interpretation. Some of these irregularities may possibly be due to unsuspected differences in relative motion and stress distribution at the interfaces.

References

[1] Frocht, M. M., *Photoelasticity*, Vol. I 1941, Vol. II, Wiley, New York, 1948.

[2] Heywood, R. B., *Designing By Photoelasticity*, Chapman and Hall, London, 1952.

[3] Drucker, D. C., "Photoelastic Separation of Principal Stresses By Oblique Incidence," *Transactions of the ASME*, Vol. 65, 1943, p. A-156.

[4] Young, D. F., "Basic Principals and Concepts of Model Analysis," *Experimental Mechanics*, Vol. 11, No. 7, July 1971, pp. 325–336.