Durability Under Repeated Buckling of Stiffened Shear Panels

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Abstract

A PARAMETERIC experimental investigation was conducted into the durability of stiffened metal shear panels subjected to repeated bucklings. The numbers of repeated buckling cycles required to crack initiation and to complete failure of the shear webs were obtained for beams with various combinations of web thicknesses, stiffener properties, and panel aspect ratios, subjected to various levels of postbuckling loads. The tests were supported by numerical analyses. Design prediction formulas were constructed, and important parameters and behavior patterns were identified.

Contents

Stiffened straight and curved panels are widely used as major structural elements in aircraft, ship, and civil engineering designs. The stable postbuckling behavior of these panels and their capability to withstand loads far in excess of their initial buckling loads may lead to considerable weight savings, if fully utilized and provided that freedom from possible fatigue problems is demonstrated.

Recent studies,[1] on which this synoptic is based, as well as airframe failures in service, have revealed that repeatedly buckled stiffened shear panels might be susceptible to premature failure due to fatigue. This can occur well within the flight envelope loads of the airframe. This mode of failure is described and discussed extensively in Ref. 1, where additional literature pertinent to fatigue and postbuckling is also analyzed. It appears that most of the current literature is concerned with the ultimate load carrying capacity and very little information is available on the complex stress field that develops in the postbuckling panels and might lead to premature cracking and failure.

The investigation summarized herein undertook the study of the capability of stiffened straight metal shear panels to withstand many repeated bucklings, far in excess of initial buckling. This included the identification of failure modes, the study of the dominant geometrical and material parameters, and the establishment of quantitative life prediction estimates.

The core of the investigation consisted of instrumented repeated buckling tests on "Wagner beams" under realistic test conditions. These were supplemented by numerical analyses with STAGS.[2] The cyclic to critical shear buckling ratios (V_{cyc}/V_{cr}) in the tests series ranged between 2.10 and 9.33, with ultimate to cyclic ratios (V_{ult}/V_{cyc}) ranging between 1.84 and 3.68. Care was taken to use load ratios within possible flight envelope loads. This necessitated a wide margin between the ultimate and buckling loads, which strongly influenced, in turn, the selection of sizes and dimensions of the test specimens (see Ref. 1.).

The use of a three-point loading system on the stiffened Wagner beams contributed towards a more realistic loading environment. More details related to the loading frame and test procedures can be found in Ref. 1.

Durability of repeatedly buckled panels in a realistic environment is a multiparameter problem on which the statistical nature of fatigue is superimposed. In this test series, the following effects were studied: 1) varying sizes of stiffeners; 2) magnitude of initial buckling loads; 3) panel aspect ratio; and 4) cycling shearing forces V_{cyc}.

The detailed test results together with the numerical results yielded by STAGS[2] and Kuhn et al.[3] are presented and compared in Tables 1a, 1b, and 1d of Ref. 1. The life span of the panels to crack initiation N_i and complete failure N_f for various cycling load ratios V_{cyc}/V_{cr} and V_{ult}/V_{cyc} are also given in Table 1c of Ref. 1.

The test and numerical results were synthesized into formulas which relate the life of the structures (represented by either N_i or N_f) to the important relevant geometrical and "physical" parameters of the problem. These are 1) ($V_{cyc} \div V_{cr}$), the well known k value of Kuhn et al.[3]; 2) (V_{ult}/V_{cyc}), ratio of ultimate to working load, which reflects the level of the cycling working load in the flight envelope; and 3) ($B^3 t/I_f$), ratio of the in-plane rigidity of the web to the in-plane stiffener moment of inertia.

The following form of simple exponential prediction formula for N_i and N_f was used:

$$N = A\,(V_{ult}/V_{cyc})^{\alpha}\,(V_{cyc}/V_{cr})^{\beta}\,(b^3 t/I_f)^{\gamma} \tag{1}$$

where A, α, β, and γ were determined from the test data, employing standard least square techniques, and are given in Figs. 1a and 1b.

The prediction formulas for N_i and N_f together with the test results for each beam type (A through E of Ref. 1) are shown in Figs. 1a and 1b. Experimental scatter of N_i and N_f around the predicted lines appears to be small, considering the inherent scatter in fatigue type data. However, the scatter of N_i is somewhat larger than that of N_f. This can be attributed to the difficulties in detecting crack initiation.

The proposed formulas include several parameters. Additional ones, depending upon the configuration (such as aspect ratio), might also play a significant role. This possibility has led to the quest for a single physical parameter which would combine the effects of some, or all, of the parameters of this multiparameter phenomenon. In this respect, V_y (the load at which local yielding takes place first) was found to be dominant. Accordingly, a prediction formula based on this parameter was proposed as follows:

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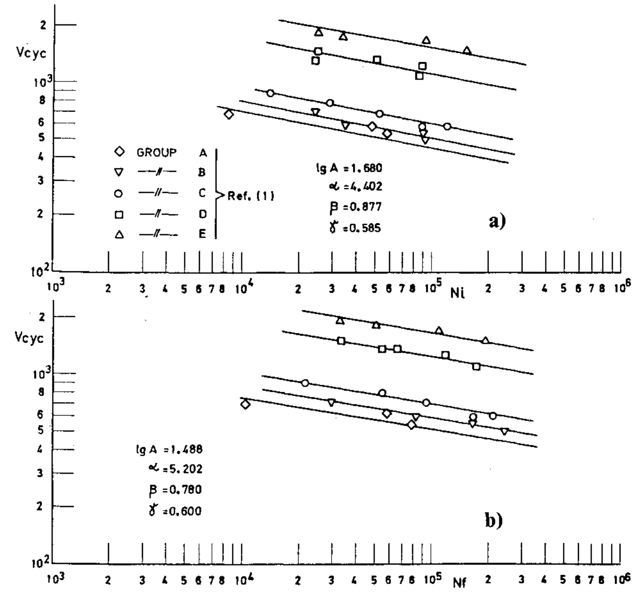

Fig. 1 Life to crack initiation (Eq. 1).

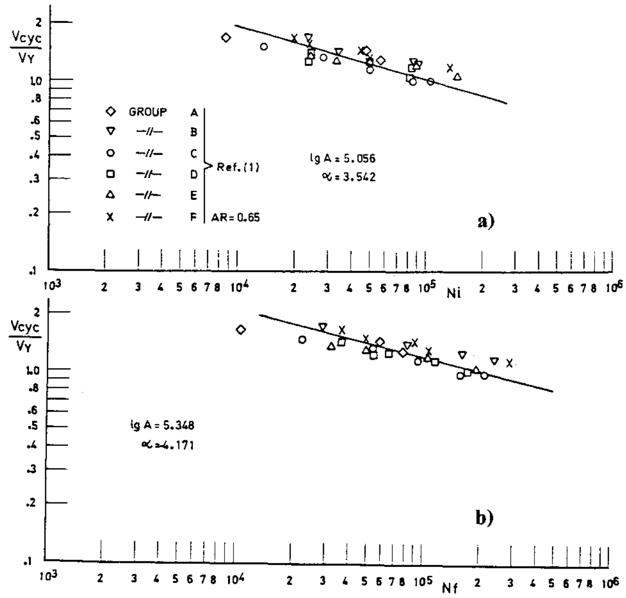

Fig. 2 Life to crack initiation (Eq. 2).

$$N=A(V_{cyc}/V_y)^{\alpha} \tag{2}$$

The values of A and α are given in Figs. 2a and 2b.

The advantage of V_y as a single physical parameter is related to the fact that modern theories of crack initiation and extension are related to the occurrence of very localized yielding due to stress concentrations. On the other hand, it is difficult to experimentally detect these highly stressed areas in order to obtain V_y. Therefore, recourse to numerical methods has to be made. In the present studies, STAGS[2] was used.

The predictions of Eq. (2), together with the experimental results for each beam type (A through E), are presented in Figs. 2a and 2b. It is observed that the trends of the scatter of the test results around the predicted lines are similar in nature to those of Fig. 1. The increase in scatter of N_f may be attributed to the fact that the dominancy of V_y decreases with crack propagation.

The predictive capability of the formulas based on V_y was also checked for beams with aspect ratio of 0.65 (group F[1]). The results are also presented in Figs. 2a and 2b. It is apparent that the use of Eq. (2) provides a good predictive capability even for this aspect ratio.

The following observations can be made regarding the results of the experimentally derived design formulas:

1) The results can be expressed in terms of three geometrical-physical parameters: (working/buckling) and (ultimate/working) load ratios, and (plate/stiffener) stiffness ratio.

2) The single physical parameter V_y, which represents the shear load at which local yielding first takes place, dominates the endurance of the panel. The life might be expressed in terms of the single ratio (V_{cyc}/V_y), which for the present configurations predicts both crack initiation and extension well, up to complete failure. V_y can be calculated with any computer code with a nonlinear elastic plate capability.

3) The number of cycles to crack initiation and failure are mostly affected by the (ultimate/working) load ratio. Ratios of 5 to 1 and more exist between the exponent of this term and the one corresponding to the (working/buckling) ratio.

4) Boosting the working load by increasing the stiffness of the frame might lead to degradation in fatigue life for the prescribed (ultimate/working) load ratio, as reflected by the value ($\gamma=0.6$) for the exponent in Eq. (1). This phenomenon stems from the local effects of stiffener rigidity on the stress concentration near the corner of the panel, where the diagonal-tension buckle interacts with the stiffener.

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