

New method of determination of spot welding-adhesive joint fatigue life using full field strain evolution

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Abstract: Fatigue tests were conducted since more than two hundred years ago. Despite this long period, as fatigue phenomena are very complex, assessment of fatigue response of standard materials or composites still requires a long time. Quite precise way to estimate fatigue parameters is to test at least 30 standardized specimens for the analysed material and further statistical post processing is required. In case of structural elements analysis like hybrid joints (Figure 1), the situation is much more complex as more factors influence the fatigue load capacity due to much more complicated structure of the joint in comparison to standard materials specimen, i.e. occurrence of: welded hot spots or rivets, adhesive layers, local notches creating the stress concentrations, etc.

In order to shorten testing time some rapid methods are known: Locati's method [1] - step by step load increments up to failure, Prot's method [2] - constant increase of the load amplitude up to failure; Lehr's method [2] - seeking for the point during regular fatigue loading when an increase of temperature or strains become non-linear. The present article proposes new method of the fatigue response assessment - combination of the Locati's and Lehr's method.

1. Introduction

Currently, aviation industries use many different complex joining techniques for structural element manufacturing, among other things - hybrid joints, e.g. [3-19]. The most popular are rivet-adhesive [3-8] and hot spot welding (HSW) - adhesive joints [4, 9, 17-18]. The hybrid joints, in assumption, are combination of good properties of each used simple joining techniques. In this article the fatigue process of HSW- adhesive joints will be analysed with application of the new testing methodology. Classically, to estimate the S-N curve (Wöhler curve) for assessment of the fatigue response it is necessary to perform experiments with at least 30 specimens, i.e. for six stress levels with application of five specimen per each stress level. Up to now, some rapid methods are also widely known i.e.: Prot's, Locati's or Lehr's, which shorten the time of testing.

The article presents the new innovative experimental method combining Locati's and Lehr's concepts. The idea rely on strains increase measurement during damage cumulative fatigue process for gradual increase of loading (Figure 2) up to the final failure of specimen. When the strain increase becomes out of linear the damage growth is enough advanced to start unstable part of its sudden uncontrolled increase in the local HSW points. This leads to immediate failure of the samples by HSW shearing.

The fatigue load spectrum, chosen for testing, represents real flight condition previously recorded by the industrial partner. The step by step loading increase during fatigue tests with specially selected



number of cycles at each level of loading (Figure 3) allows for effective shortening of the testing time, getting reasonable estimation of fatigue strength.

Obtained results denote that full-field strain measurement requires only few specimens to obtain fatigue load capacity.

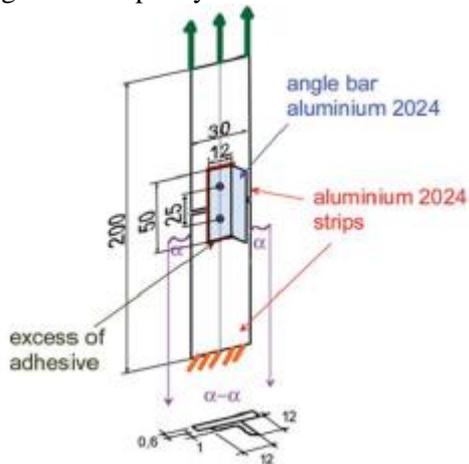


Figure 1. Specimen shape and dimensions

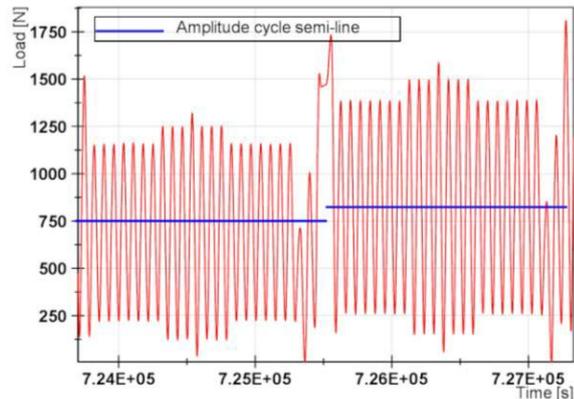


Figure 2. Fatigue load spectrum and load increase moment

2. Experimental setup and new testing methodology.

The experimental setup consists of 3 elements:

1. 25 kN servohydraulic system MTS (USA),
2. 2 Digital Image Correlation (DIC) systems ARAMIS (Germany),
3. National Instrument data acquisition system (USA).

All elements of the testing stand were synchronically triggered during loading program, to get full information about fatigue process of the experimental samples.

The applied load spectrum (Figure 2) corresponds to 2 hour of the airplane flight including starting, ascending, descending and landing. Dynamic loading frequency of servohydraulic system MTS was equal to 23 Hz. The actual values of the carrying load and stroke displacements were recorded with frequency of 1 kHz.

The applied 2 DIC systems ARAMIS allowed for constant monitoring of the deformation process of the specimen from the front and rear sides. After monitoring of displacement fields during fatigue tests the DIC system enables calculation of the major and minor strains. The strains distributions were particularly assessed in the spot areas, where the damage initiation and further propagation takes place, leading to the failure of the hybrid joints.

The whole testing program for estimation of fatigue response of the samples is presented in Figure 3. The fatigue process starts at level 1.5 kN, which denotes about 40% yield force P_y , Figure 7. The whole program is divided into 24 loading levels with gradation 75 N. Each loading level consists of 104 cycles, similarly to Locati's method. In the last part of loading program, starting from level 2.775 kN the number of stages increases to 200 (every 50 cycles), as in this part of experiment damage processes initiates and finally leads to failure of the samples. Maximal loading level reached by specimens were equal to 3.25 kN. This value is much below the yield force P_y .

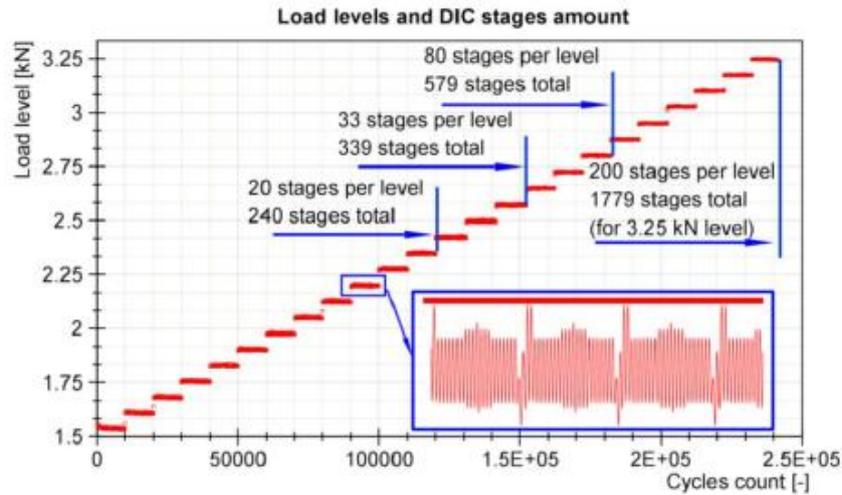


Figure 3. Loading program as a function of cycles amount and DIC stages amount

3. Specimens and HSW microscopic analysis

The specimens, Figure 1, were delivered by industrial partner PZL Mielec (Poland). All specimen were made of aluminium alloy 2024 T352. Each specimen consisted of two sheets and an angle bar, which were initially joined by 2 HSW and further they were strengthened by the Epodur adhesive. Material properties - both for aluminum and an Epodur adhesive - are presented in Table 1.

Figure 4 presents schematically spot weld cross section. The size and shape of the fusion zone (FZ) is crucial for HSW joint. Figure 5 shows the real cross section of the spots. One can observe irregular and not symmetric shapes HSW and the FZ material does not differ of the original material.

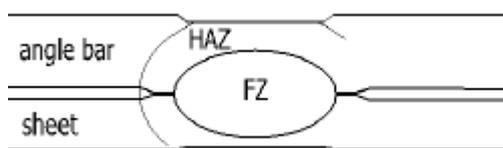


Figure 4. Schematic view of the spot cross section, FZ - Fusion Zone, HAZ - Heat Affected Zone

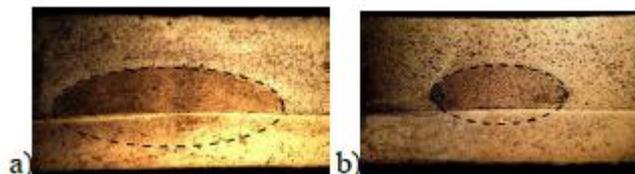


Figure 5. Cross section of two real fusion zones (FZ)

The failure of the hybrid samples starts from the damage of the adhesive layers. The final fatigue failure of the specimen is by shearing of HSW points. Typical fatigue failure mode is presented on Figure 6. Most of the specimens were damaged according to this failure mode.

Table 1. Material properties of the Epodur and aluminum sheets

Parameter	Epodur	2024 T352
E [MPa]	1861	66134
ν [-]	0.39	0.30
Rm [MPa]	40.7	431
A [%]	4.26	20.2

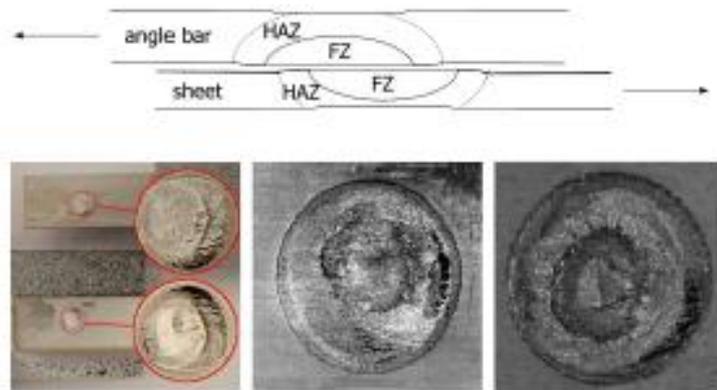


Figure 6. Typical fatigue failure mode

4. Results

Quasi-static response of the hybrid joints (Figure 7) were analyzed by authors in [17]. All fatigue loadings were conducted below yield force P_y point. One can notice that application of the Epodur adhesive leads to increase of the load carrying capacity about 2 times.

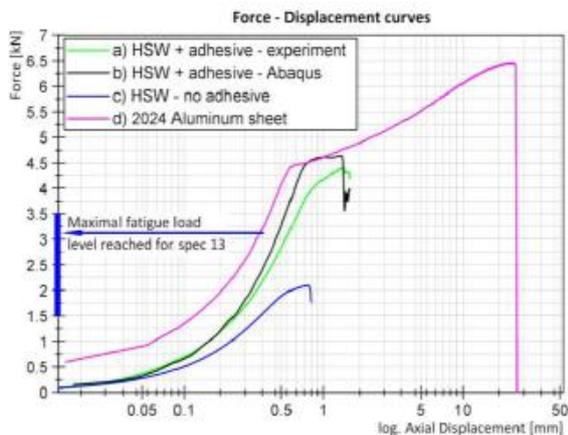


Figure 7. Force - displacement diagram for quasi-static tests

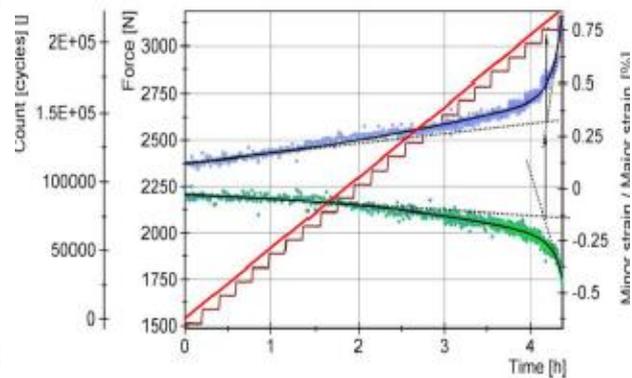


Figure 8. Fatigue test analysis: cycles amount (red), load levels (brown), major strain (blue), minor strain (green) and approximation curves (black)

Experimental observations of the last stage of the fatigue process, just before failure (Figure 8-10), clearly showed that highest strain concentration (higher than 1%) took places in the spots area. Each curve representing average strain change during fatigue process - computed from welded spot area - is very similar to exponential function. For selection of the best approximation function - the coefficient of determination (R^2) was taken into account, which should be at least 0.85.

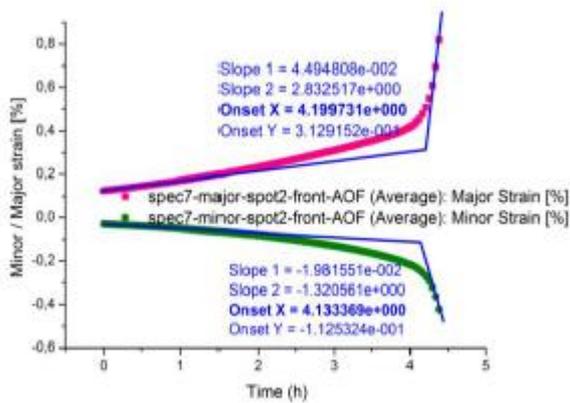


Figure 9. Idea of Lehr's method - two tangent lines analysis

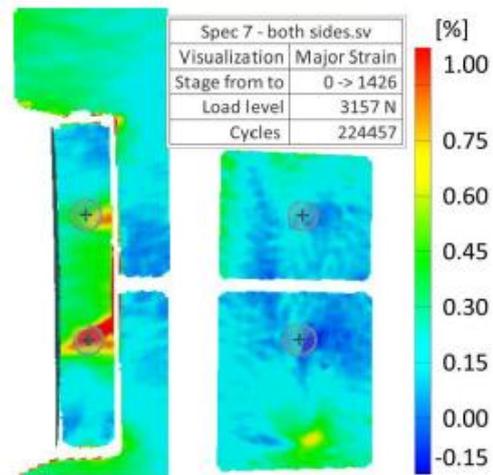


Figure 10. Major strain analysis - last stage of the fatigue test just before failure

5. Conclusions

The new time-saving rapid method for determination of safe levels of loads, cycles amount or displacements was presented in the article. The experimental setup consisting of 2 DIC systems was used to monitor the increase of the local full field strain in the most efforted points of the hybrid joints for the step by step loading increment. The effective application of the method was demonstrated on the analysis of the complex shape hybrid specimens under fatigue.

The proposed approach creates very effective tool for estimation of the fatigue response of different structural elements as well as modern multiphase composite materials, e.g. [19-23]. The analysis comprises a low cycle or even high cycle fatigue problems and can be used in other fields of research. The method is flexible and can be modified to obtain more accurate results with application of more loading levels, if required.

The experimental evidences will be extended to numerical modeling of the gradual fatigue degradation, including different damage models, e.g. [24-32].

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