Experimental Stress Analysis

PROCEEDINGS OF THE
8TH INTERNATIONAL CONFERENCE

1986

Experimental Stress Analysis

Proceedings of the VIIIth International Conference on Experimental Stress Analysis, Amsterdam, The Netherlands, May 12–16, 1986
Organized by: Netherlands Organization for Applied Scientific Research (TNO) on behalf of The Permanent Committee for Stress Analysis

edited by

H. WIERINGA

TNO-IWECO
Delft, The Netherlands

1986 **MARTINUS NIJHOFF PUBLISHERS**
a member of the KLUWER ACADEMIC PUBLISHERS GROUP
DORDRECHT / BOSTON / LANCASTER

Distributors

for the United States and Canada: Kluwer Academic Publishers, 190 Old Derby Street, Hingham, MA 02043, USA
for the UK and Ireland: Kluwer Academic Publishers, MTP Press Limited, Falcon House, Queen Square, Lancaster LA1 1RN, UK
for all other countries: Kluwer Academic Publishers Group, Distribution Center, P.O. Box 322, 3300 AH Dordrecht, The Netherlands

Library of Congress Cataloging in Publication Data

ISBN 90-247-3347-2 (hardback)

PRINTED IN THE NETHERLANDS

Preface

Designing and manufacturing structures of all kinds in an economic and a safe way is not possible without doing experimental stress analysis. The modernity of structures, with their higher reliability demands, as well as today's more stringent safety rules and extreme environmental conditions necessitate the improvement of the measuring technique and the introduction of new ones.

Although theoretical/mathematical analysis is improving enormously, an example of which is the finite element model, it cannot replace experimental analysis and vice versa. Moreover, the mathematical analysis needs more and more accurate parameter data which in turn need improved experimental investigations. No one can do all those investigations on his own. Exchange of knowledge and experience in experimental stress analysis is a necessity, a thing acknowledged by every research worker. Therefore, the objective of the Permanent Committee for Stress Analysis (PCSA) is to promote the organization of conferences with the purpose disseminating new research and new measuring techniques as well as improvements in existing techniques, and furthermore, to promote the exchange of experiences of practical applications with techniques.

This VIIIth International Conference on Experimental Stress Analysis on behalf of the PCSA is one in a series which started in 1959 at Delft (NL), and was followed by conferences at Paris (F), Berlin-W, Cambridge (UK), Udine (I), Munich (FRG) and Haifa (Isr.). Such a Conference will be held in Europe every fourth year, half-way bewteen the IUTAM Congresses. Close co-operation exists between PCSA on the one hand and the Gemeinschaft für Experimentelle Spannungsanalyse (GESA) of the VDI/VDE Gesellschaft Mess- und Regelungstechnik (FRG) and with the Society of Experimental Mechanics (SEM) on the other.

In this book the papers have been collected that will be discussed at the VIIIth Conference on Experimental Stress Analysis.

The topic of the Conference is "Current Developments and Perspectives in Experimental Mechanics". The PCSA expresses its thanks to the authors who took the trouble to forward papers comprising their experiences in the field of experimental mechanics and hopes that these contributions will fulfill your expectations and help you in solving your stress analysis problems. Moreover, PCSA expects the Conference to contribute to the development and deepening of personal contacts between the participants from all over the world.

It also likes to express its thanks to the Paper Selection Committee members for their evaluation of the papers presented and for their advice and support in drafting the programme. Acknowledgement of thanks is also expressed to the Netherlands Organization for Applied Scientific Research (TNO) and in particular to the fellow-workers of the TNO Corporate Communication Department and those of TNO-IWECO; Institute of Mechanical Engineering. Without their efforts this Conference would not have been possible.

May 1986
H. Wieringa
Chairman Permanent Committee
for Stress Analysis

Organizing Committee

H. Wieringa, Chairman
H. van den Berg, Secretary

Permanenent Committee for Stress Analysis

H. Wieringa (The Netherlands)-Chairman
S.I. Andersen (Denmark)
V. Askegaard (Denmark)
M.C. Azevedo (Portugal)
A. Berkovits (Israel)
A.A. Betser (Israel)
R. Bourgois (Belgium)
A. Bray (Italy)
R. Fidler (United Kingdom)
K. Fristedt (Sweden)
J.J. Geerlings (The Netherlands)
M. Gibstein (Norway)
K.H. Laermann (Federal Republic of Germany)
A. Lagarde (France)
A.R.G. Lamas (Portugal)
A. Martin (France)
Chr. Rohrbach (Federal Republic of Germany)
W. Schumann (Switzerland)
P. Stanley (United Kingdom)
D.S. Theocaris (Greece)
M.E. Tschinke (Italy)

Paper Selection Committee for the VIIIth International Conference on Experimental Stress Analysis

H. Wieringa, Chairman (The Netherlands)
K.H. Laermann (Federal Republic of Germany)
P. Stanley (United Kingdom)
J.J.P. Geerlings (The Netherlands)
A.U. de Koning (The Netherlands)

Scientific Secretariat / Editor

H. Wieringa
TNO-IWECO
P.O. Box 29
2600 AA Delf
The Netherlands
Phone: +31/15 608608
Telex: 38192 iweco nl

TABLE OF CONTENTS

MEASURE AND DESIGN OF STRESSES IN ADHESIVE BONDED TRUSSES : EXTENSOMETRICAL AND LASER-ELASTICIMETRICAL METHODS

L. BEN AICHA*, Y. GILIBERT**, A. RIGOLOT***

E.N.S.T.A. - L.M.E.
Groupe Composites et Collage
Centre de l'Yvette, Chemin de la Hunière
91120 PALAISEAU

1. INTRODUCTION

Used since the remotest antiquity, the bonded assemblage has been developed in the technological field since the beginning of the 20th century.

However, the fondamental researches about this way of bonding dates back to, at the very most, forty years. Coupled with important progresses in joint design and improved knowledge of bonding processes, the result is an ever growing variety of adhesive bonded assemblages, depicted for instance in references [1].

One of the aims of this paper is to show with the help of examples, that the extensometrical method with electrical gauges is suitable for the study of the mechanical behaviour of bonded structures.

This method, elaborated by GILIBERT [2] in the years 1971-73, allowed to validate a finite elements method [5].

In 1977-78, GILIBERT and RIGOLOT have developed an analytical theory of double lap bonded joints by using the method of matched asymptotic expansions [3] [4] ; since then, the comparison between measurements and computations allowed conclusive progress with regard to this complex domain of solid mechanics.

In 1985, with the collaboration of FERRE [6], BEN AICHA and GILIBERT used a laser-photoelasticimetry method to measure the stresses in double lap bonded joints with the aim of confirming theoretical results.

2. PREPARATION OF THE SURFACE AND MEASUREMENT OF THE GEOMETRY

2.1. Properties of the Adherends

A low carbon steel (0.18 % carbon ; XC 18 French standard equivalent to SAE-AISI 1017) was used for the adherends of the specimens studied. The properties of the steel were controlled using mechanical measurements and microscopic observations. The Young's modulus (E_T = 207 700 MPa) and the Poisson's ratio were determined using tension test with strain gauges at a very low strain rate ($\dot{\varepsilon}$ about 10^{-6} s^{-1}) on steel specimens with 100 mm2 square cross section and 250 mm length. The Brinnell hardness (HB = 210) test showed the uniform quality of the material, whereas microscopic observations indicated a ferritic microstructure.

*Thésard ENSTA/LME/GCC

**Chef du Groupe Composites et Collage, Maître de Conférences, Docteur ès Sciences

***Conseiller Scientifique du G.C.C., Professeur des Universités à Reims

Wieringa, H (ed), Experimental Stress Analysis. ISBN 90-247-3346-4.

2.2. Preparation of the Rough Adherends, Finishing and Blasting

A shaping machine with a traversing tool was used in the preparation of the rough adherends.

This was followed by milling and after which a grinding was effected with a horizontal surface grinding machine under different conditions : coarse or fine grain grinding wheels. For all these operations, machining conditions (speed, feed, depth of cut, lubrication, sharpening of the tools) were strictly controlled and are described in Reference 2,Chapter 4

The finishing procedure for some of the specimens was completed with sand blasting under four conditions using different particle diameters (115, 169, 282 and 423 µm) or with shot blasting. The particles with a 115 µm diameter were made of high purity white alumina (Al_2O_3>99,5 %), whereas the particles with diameters of 423, 282 and 169 µm were of brown corundum, i.e. less pure alumina (composition : Al_2O_3>94 % ; TiO_2<2.5 % ; SiO_2<.5 %). The blasting pressure used was 0.4 to 0.5 MPa. The sand jet was inclined at 60° from the specimen surface and displaced at a speed of 24 mm s^{-1}. The shot blasting was conducted with iron shots 1 mm in diameter.

In this paper, the various surface states are designated as follows :
RF - fine ground state ; RFS - fine ground sand blasted state ;
RG - coarse ground state ; RGS - coarse ground sand blasted state ;
RGG - coarse ground shot blasted state.
The numbers following RFS and RGS designate the particle mesh size.

2.3. Measurement of the Surface Roughness Parameters

The surface profiles were determined using probes with an air bearing of 25 µm and 750 µm travel distances. The specimens used had the same section as the adherends and were machined and treated at the same time under the same conditions. The surface profiles were measured, before and after blasting, along reference paths, the ends of which are marked with two notches remaining after blasting.

Data were recorded and processed by a computer to determine the various parameters of the surface defects describing the total profile, roughness and waviness. The calculations were done using a method developed by B. Scheffer of RENAULT (FRANCE).

We observed that the surface roughness parameters alter very quickly during the first few seconds of blasting and do not change after a while. We selected a time lapse of 30 seconds which ensured a stable state of these parameters.

Measurements showed that the surface roughness parameters are not dependent on the direction of measurement for blasted states, whereas condition as ground showed some anisotropy.

Reference 2, chapiter IV, table IV.1 presents values of the surface roughness parameters for the various surface states studied. These are the total depth of roughness, R_t ; the average depth of roughness, R ; the maximum depth of roughness, R_{max} ; the roughness levelling depth, R_p ; the arithmetical mean deviation from mean line of roughness, R_a ; and average spacing of roughness, A_R.

From these data, it can be seen that the surface roughness parameters for sand blasted states depend on both the initial grinding and the mean diameter of the particles used for blasting. For all surface preparations, the maximum depth of roughness R_{max} is very close to the total depth R_t, which indicates that surfaces have no aberrant defects of roughness and are consequently fairly homogeneous ; for the fine ground state, the roughness parameters increase steadily with the particle diameter whereas for

the coarse ground state these increase notably only for a diameter superior to 200 µm.
Other surface defect parameters were computed but proved of little importance as far as the mechanical properties of the joints are concerned. However, they confirmed that the prepared surfaces had well defined and reproducible parameters.

2.4. Properties of the adhesive

We used the commercial adhesive, Eponal 317, of Sonal, France, which is a two component system (an epoxy resin containing mineral fillers and a hardening agent). It was processed at room temperature ; at such temperature, about 20 minutes are available for use and polymerization rate reaches 90 % within 2 hours.
We determined its mechanical, physical, structural and chemical properties
The elastic constants were measured at room temperature (20°C) using two methods. Tensile test using strain gauges and a very slow loading rate ($\dot{\varepsilon}$ about 10^{-6} s^{-1}) showed an elastic brittle behavior. Using traction test the Young's modulus was found to be 5800 MPa, the Poisson's ratio was 0.327 and the strength was 30 MPa ; whereas ultrasonic measurements gave 5940 MPa for the Young's modulus and 0.323 for the Poisson's ratio. The measured density was 1.433 kg dm^{-3}.

3. DESIGN AND MANUFACTURE OF THE TEST-SPECIMENS-LOADING CONDITIONS

We used specimens with two double-lap joints. One of these double-lap joints was used for strain measurements. The other joint, which was tightened transversely by a binding clip, ensured axial and uniform load in the adherends, while the clip eliminated any local bending. The extremities of the test-specimen were fixed on a universal testing machine by knee joints. In fact, this design of the specimen ensured symmetrical fractures in the tested part, and the clip decreased considerably the statistical deviation in the measurements, as shown in Reference 2, Chapter 2. Figure 1 shows a schematic view of the specimen.
The parts (10 mm x 4.5 mm cross-section for parts 2' ; 10 mm cross-section for parts 1') were produced at a ± 0.01 mm tolerance. The length of the overlap in the tested part of the specimen was 88 mm. A thickness of 0.5 mm was selected for the adhesive joint and controlled by gauged spacers. Preliminary tests, described in Reference 2, Chapter 11, showed that this thickness gives the best mechanical behavior for these dimensions of the metallic parts and this length of the joint.
The test-specimens were loaded in tension at a slow rate (1000 N per minute) at room temperature (20°C).

4. PRINCIPLE OF THE MECHANICAL MEASUREMENTS

Since mechanical quantities inside the joint cannot be obtained directly, we used electric strain-gauges placed at different points on external surfaces of the metallic adherends. Figure 1 shows the position of the gauges ; their distances from the middle of the joint are as follows :
- gauge 1 : + 37 mm
- gauge 2 : - 18.5 mm
- gauge 3 : 0
- gauge 4 : + 18.5 mm
- gauge 5 : + 37 mm

The positioning of the gauges is described in detail in Reference 2, (Chapter 5).

A sensitive and precise (± 0.25 %) bridge (VE 20 Micromeasurement) was used.
Figure 2 shows typical strain gauge recordings for a ground sans blasted state. Other recordings are given in Reference 2.
Principle of the mechanical Measurements is described by references 2 and 7

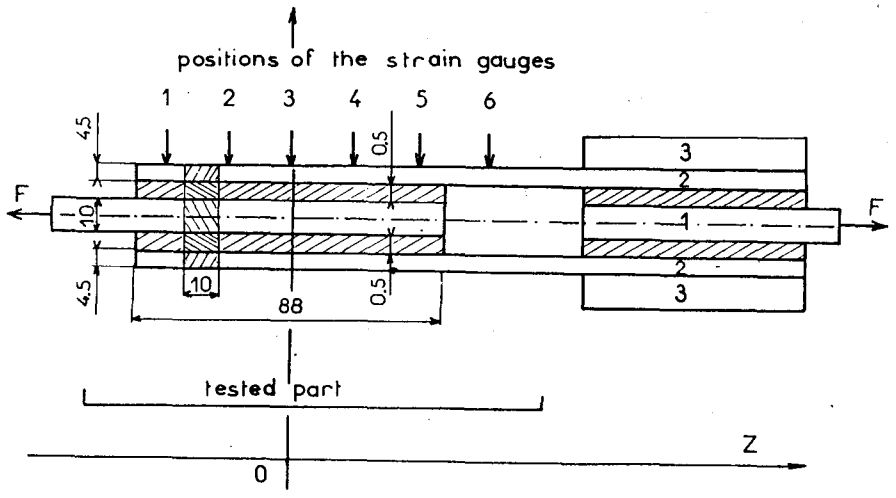

Figure 1. Schematic view of the test-specimen (dimensions in mm). A view of the cross-section is superimposed between gauges 1 and 2. 1' and 2' : adherends ; 3' : binding clip.

Visual and microscopic observations of the fractured specimens have confirmed that in the central part of the joint a progressive shear fracture occurs inside the adhesive ; at the ends of the joint one can see either a shear fracture inside the adhesive or an adhesive failure between the adhesive and the metallic adherend along the upper or lower face, induced during the final phase of the fracture.
These facts differentiate the ground sand blasted state from the ground state, which showed predominantly metal-resin adhesive fractures.
The various stages for the ground sand blasted states, (i) elastic behavior, (ii) initiation of micro-cracks, (iii) coalescence of the micro-cracks, (iv) stable propagation of the cracks, and finally, (v) unstable propagation up to final fracture, proved to be absolutely reproducible (Reference 2, Chapter 8).
These experimental results can be partly explained by the various theoretical analyses [3, 4, 8], which have analyzed stress fields in adhesive joints. However, these theoretical analyses, which are based on continuum mechanics and use idealization of interfaces, cannot explain the significant differences observed using the above measurement procedure, and are presented below.

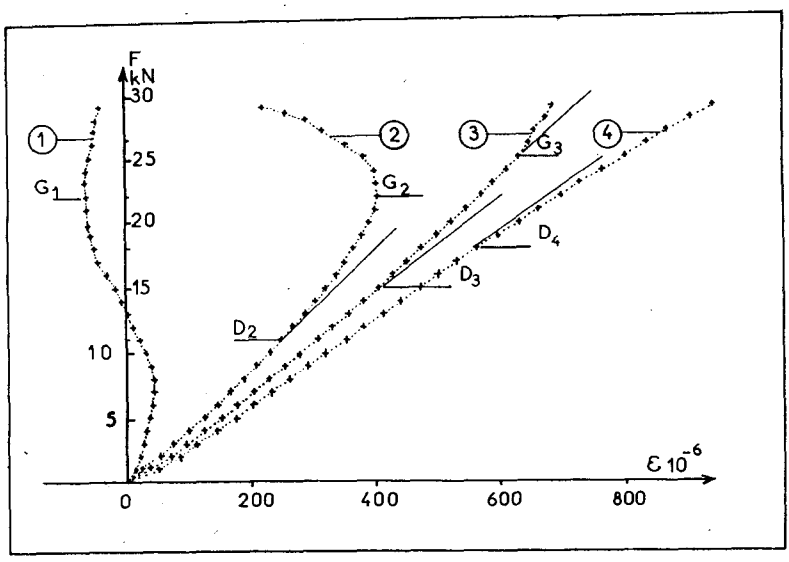

Figure 2. Strain versus tensile load for a ground sans blasted state (outputs of gauges 1-4). Non-linearity occurs over point D_2.

5. EFFECTS OF ROUGHNESS ON MECHANICAL RESULTS

Here are presented the effects of roughness on the three typical mechanical parameters : elastic limit (crack initiation threshold), crack propagation threshold, and ultimate strength.

We found that roughness can be adequately represented by using the total depth of roughness R_t.

We observed a very small scattering in the measured values, which gives proof of the importance of our careful and well-defined process in preparation and testing. Deviation in the results is generally higher for the propagation threshold and the ultimate strength than for the elastic limit. Further, deviation in the ultimate strength is higher for non-blasted surfaces than for blasted surfaces (Reference , Chapter 8). Typical values, corresponding to the results presented in Figure 3, are (i) 0.25 kN for the crack initiation threshold (about 12 kN), (ii) 0.5 kN for the crack propagation threshold (about 24 kN), and (iii) 0.5 kN for the ultimate strength (about 30 kN).

For the sand blasted states, we found that the mechanical parameters were influenced by the initial grinding and the roughness, which is related to the sand particle size.

The fine grinding is equivalent or better than the coarse grinding for the three mechanical parameters ; it gave better values for the elastic limit with all diameters.

For both types of grinding, we observed that the strain measurements given by the gauges at the external surface of the adherends were significantly smaller (for any position) and more uniform along the specimen, when the surfaces were prepared using particles with a diameter of 169 µm. Further-

more, this preparation shows the best values for the three mechanical parameters.

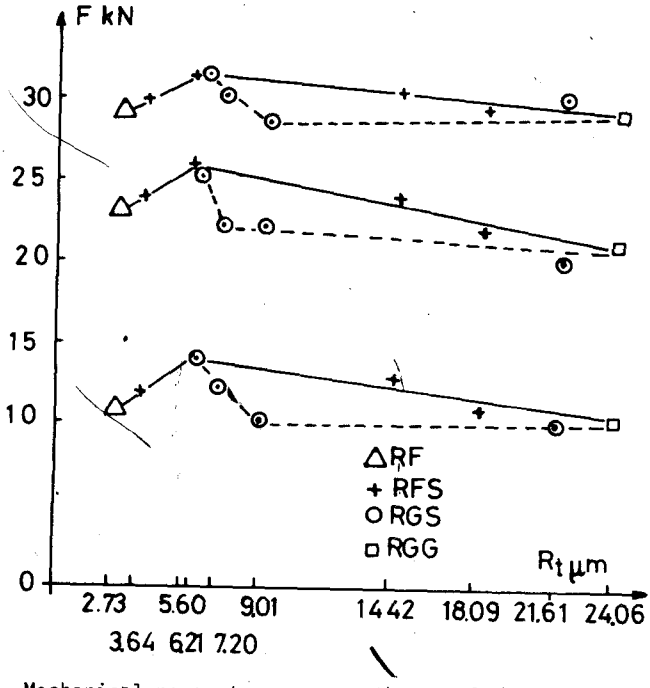

Figure 3. Mechanical parameters versus the total depth of roughness : from the bottom, (i) crack initiation threshold, (ii) crack propagation threshold, and (iii) ultimate strength. For fine grinding without blasting (RF) the values are in accordance with the extrapolation (with respect to the roughness) of those obtained for fine grinding with blasting (RFS).

Figure 3 summarize the results. Almost all of the plotted points represent the mean value of four tests. In Reference 2, Chapter 9, one can find the curves representing F versus the other roughness parameters, R_a, R_p, R ; they have the same behavior as the curves in Figure 6.
Figure 3 shows that for fine grinding, with or without blasting, the three mechanical parameters reach a maximum value when the total depth of roughness equals 5.6 µm. It seems possible to associate this property with the fact that the total depth of roughness is approximately the size of the fillers in the resin.
No precise trends can be found in the case of coarse grinding.

6. COMPARISON BETWEEN THEORETICAL AND EXPERIMENTAL RESULTS

For an optimal state (e_J = 0,5 mm), we see on figure 4 a good correlation in the elastic domain between theoretical results [3] [4] [8] and experimental measures. Some difference appears in the neighbourhood of the free end of the upper adherend : it was impossible to introduce in computations the effects of the angular singularities in these regions.

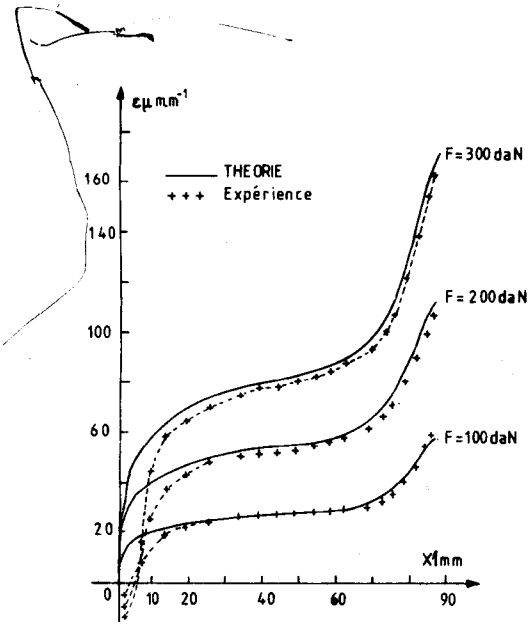

Figure 4. Longitudinal deformations versus distance of the measurement. Localization from the free ends of the adherends (T_1 and T_2, figure 5)

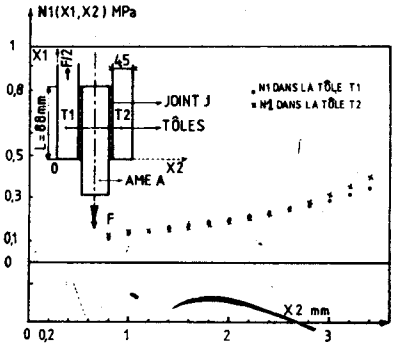

Figure 5. Principal stresses in adherends T_1 and T_2 at abscissa X_1 = 10,5 mm versus the thickness coordinate X_2.

7. STRESS MEASUREMENTS BY A LASER PHOTOELASTICIMETRICAL METHOD

The truss is made in the same way that the one depicted in Figure 1, whose adherends in polycarbonate (PSM-1) are joined by PC1 adhesive (Vishay Micro-mesures, Young's modulus : $E_{PSM.1}$ = 2400 MPa ; E_{PC1} = 3150 MPa. POISSON's ratio : $\nu_{PSM.1}$ = 0.38 ; ν_{PC1} = 0.36 ; Figure 5.)

Principal stresses, measured by an automatic laser-photoelasticimeter, are presented in Figure 6. It's to be noted that the shape of the curve in figure 6 is similar to the experimental one depicted in figure 4.,especially in the neighbourhood of the free edge of the adherend.