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Investigation of the Crack Growth on the Cruciform Specimens with Sharp Notches under Biaxial Loading

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ABSTRACT: *Experimental investigation into fatigue and fracture of plane cruciform specimens made from Plexiglass is presented. Central artificial notch with inclination angle of 90^0 or 45^0 with respect to the specimen arms, served as a stress concentrator to localise multiaxial (tension, compression and shearing) damage conditions. Numerical results, obtained by means of the boundary element method BEM, were used to calculate stress intensity factors for various loading conditions and notch configurations. Physical interpretation of fatigue initiation period and other phenomena concerned with damage process are also discussed.*

Notation

$2a_o$	- total length of the initial artificial notch
Fm_x, Fm_y	- external forces applied to the specimen arms
K_I, K_{II}	- stress intensity factors for Mode I and II causing multiaxial damage of slant notch
K_{Ic}	- critical value of the stress intensity factor for Mode I
K_{Ix}, K_{IIx}, K_{Iy}, K_{IIy}	- stress intensity factors resulted from Fmx and Fmy
PXST4	- specimens with the notch inclination angle of 45^0,
PXST9	- specimens with the notch inclination angle of 90^0,
$R = Fm_y/Fm_x$	- loading ratio
η_1, η_2	- initial fracture angles for both notch extremes, measured with respect to the notch plane

Introduction

Internal flaws and cracks in structural materials may cause damage to the construction element subjected to various loading conditions, and significantly decrease its durability. Multiaxial stress states make predictions of brittle fracture and fatigue life very complicated. Propagating cracks usually follow a curvilinear path, which depends on many factors as material properties and loading. The descriptions of damage process and simple criteria for its modelling are of great practical importance.

The present paper deals with experimental and numerical investigation on fatigue and fracture of plane cruciform specimens with central notch and subjected to multiaxial loading conditions with various tension-tension, tension-compression and tension-shear ratios. Initial periods of brittle fracture and fatigue crack initiation process as well as crack paths have been carefully studied using also video technique.

Experimental procedure, material and method

Experimental tests were carried out using a stand, specially designed for independent loading of cruciform specimens in both perpendicular directions, according to histories of generated random signals. The stand (shown in Fig. 1) consists of hydraulic supply and loading systems, as well as signal generation, control, measuring and data processing systems. However its normal application is concerned with a random non-proportional fatigue tests, in the present study only proportional in-phase load-control signals have been generated in both monotonic and variable loading conditions. Fatigue tests were carried out with constant amplitudes for different proportions between maximal stress values in both directions. More details concerned with the stand can be found in ref. (3).

Experiments were carried out using cruciform specimens made from 5 mm thick plexiglass plates fixed carefully with bolts and soft washers to the hydraulic elements of the testing machine. Two groups of specimens were prepared. One with a central longitudinal notch and the other with inclined notch, as shown in Fig. 2.

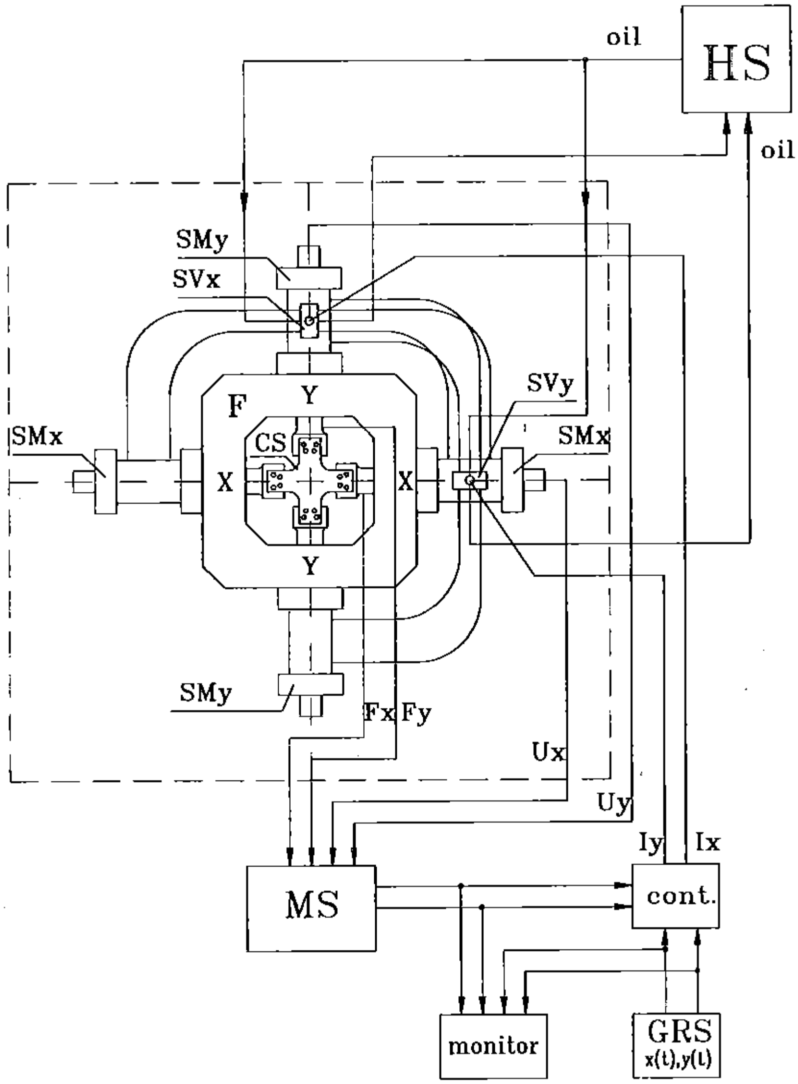

Fig.1. The scheme of the test stand for fatigue test under biaxial loading.

HS-hydraulic supply, SM-servomotor, SV-servovalve, F-frame, CS-cruciform specimen, u-displacement signals, I-controlling signals, F-loads, MS-measuring system, GRS-generator of signals, Cont.-control system.

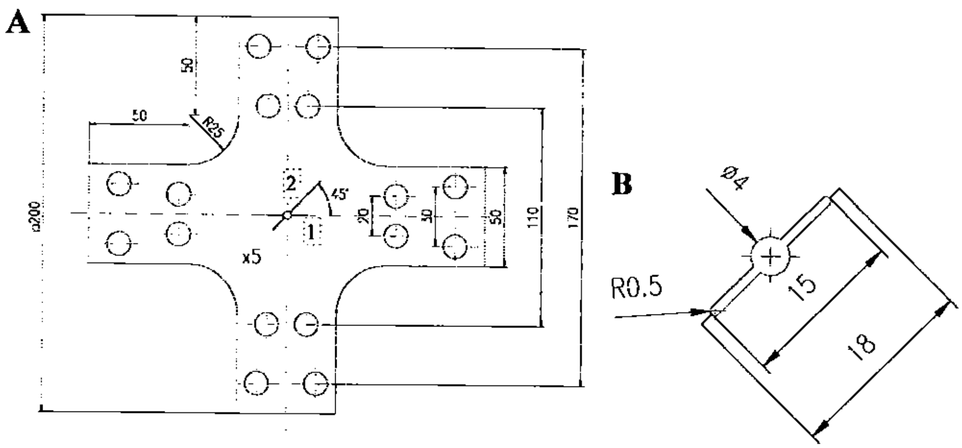

Fig. 2. Specimens with central stress concentrators in two versions (1) and (2) -A, and geometry of notch - B used in experiments

The first type of the concentrator, located colinearly with the specimen arms (fig. 2A - 1), served for investigating the influence of longitudinal tensile and compressive loads, together with different perpendicular components, on critical forces causing fracture to the element.

The second type of notch, inclined by 45^{o} arms (fig. 2A - 2), was applied to investigate effects of tensile-shearing and compression-shearing realised by changing proportions between external loads acting on the specimen in both perpendicular directions. Both types of notches have been made in such a way that a small free distance remained between their faces. This made them opened even for perpendicular compressing loads and negative values of the stress intensity factor K_I were possible.

Fatigue tests have been carried out with loading amplitudes slightly below the critical ones making the fatigue crack to propagate in a stable manner. All other details concerned with monotonic loading remain valid for fatigue tests.

Numerical analysis of the cruciform specimens

The boundary element method implemented in software program CRACKER, ref. (6), was used in numerical modelling of the cruciform specimens with central notches, in order to determine stress intensity factors for various biaxial loading. One example of such a model is presented in Fig. 3.

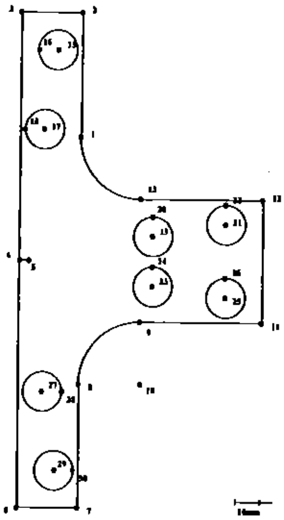

Fig. 3. Boundary element model of the cruciform specimen with a central longitudinal notch

Numerical results have shown an important influence of the longitudinal compression on K_I. Such a load produces 20.8% of K_I value compared with the same perpendicular tension. Theoretically, in an infinite plate there is no effect of longitudinal load on K_I. However, in this case the shape of the specimen makes K_I value significantly high. It means that longitudinal load is important in estimating the critical fracture conditions. The following relations between the force and K_I is obtained:

0.25 [kN] 0.134 MPa $m^{0.5}$ for $2a_0$= 18mm for perpendicular load

0.25 [kN] 0.028 MPa $m^{0.5}$ for $2a_0$= 18mm for longitudinal load

Numerical analysis resulted also very useful in cases of 45^o notch. If the force acts only in one direction, there is a constant proportion between K_I and K_{II}, i.e. K_I/K_{II}= 0.67, where

0.25[kN] K_I = 0.054 MPa $m^{0.5}$ for $2a_0$= 18mm

0.25[kN] K_{II} = 0.080 MPa $m^{0.5}$ for $2a_0$= 18mm

Making use of the above expressions, any external loads Fm_x and Fm_y applied simultaneously to the cruciform specimen have been transformed into stress intensity factors K_I and K_{II} for both types of stress concentrators.

Experimental results and discussion

Experimental tests have been carried out under load-control conditions with loading sequences recorded during the whole test. Due to the transparency of the material many special effects was able to be registered using video camera.

Both technics made possible to reproduce some characteristic damage processes: brittle fracture due to the monotonic load consisted in two steps, appearing one after another in a period depending on the loading rate. Typical loading sequence of PXST4-05 specimen is shown in Fig. 4. After the first fracture, a considerable drop of forces can be observed. Since the load approaches approximately the same value - secondary, brittle fracture appears and the crack propagates through the all element. Some observations made possible to see the first crack appeared as a semi-elliptic surface with the major axis equal to the width of the element (5 mm).

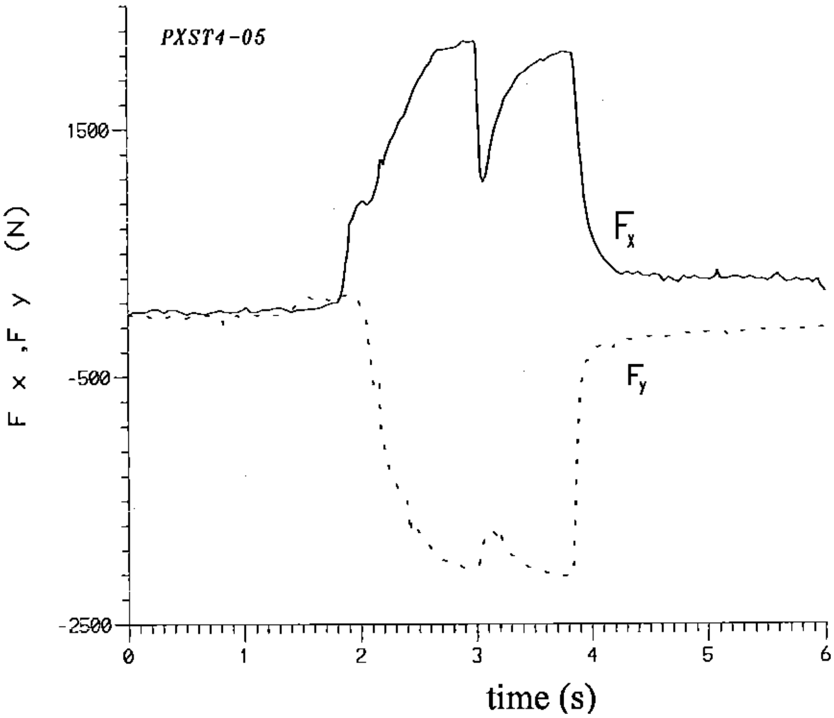

Fig. 4. Monotonic loading sequence during fracture of the PXST4-05 specimen

It is probable that the fracture conditions are not the same along the straight front of the notch and the first cracking just "equalises" damage conditions in the whole curved line of the crack front. The surface of this crack is not perfectly plane. Many longitudinal grooves can be observed terminating on the semi-elliptic crack front. Possibly, the first fracture is not formed by a simple separation of both sides. Inclined longitudinal valleys suggest that shearing stresses play an important role, so the mixed-mode I and III state contribute locally to form it. In this case a "global critical plane" - normal to the specimen surface - may be distinguish from the "local" ones, tangential to valley surfaces.

Critical forces that produce brittle fracture under the monotonic loading are shown in Table 1 and Table 2 for longitudinal and inclined notches respectively. Corresponding critical stress intensity factors, obtained numerically using BEM, and microscopic measurements of the fracture angles η obtained directly from the broken specimens, are also included.

Table 1. Results for monotonic loading of PXST9 specimens

spec. No.	$2a_o$[mm]	Fm_x[kN]	Fm_y[kN]	R	K_{Ic}[MPa m $^{0.5}$]	η^o
PXST9-02	22.0	2.06	1.91	0.93	0.99	0
PXST9-04	17.5	2.25	2.15	0.96	0.95	0
PXST9-06	16.6	1.62	-1.48	-0.93	0.98	0
PXST9-08	16.8	2.50	3.77	1.51	0.88	0
.PXST9-10	17.6	1.04	-2.82	-2.71	0.86	0
PXST9-12	18.5	1.82	.0.0	0.0	0.99	0
PXST9-14	18.4	0.0	-7.20	-∞	0.82	0

For the mode I (Table 1) critical stress intensity factors K_{Ic} are close together and the smallest values appear only when strong longitudinal compression takes place. It is possibly due to the influence of the nominal negative stresses (non-singular terms of the stress field near the notch tip) and their contribution to the damage.

From Table 2 it can be seen that during mixed-mode loading conditions, critical values of K_{II} are unexpectedly high with respect to that for K_I, especially for accompanied negative values of K_I.

Table 2. Results for monotonic loading of PXST4 specimens

spec. No.	$2a_0$[mm]	Fm_x[kN]	Fm_y[kN]	K_I[MPa m$^{0.5}$]	K_{II}[MPam$^{0.5}$]	η_1^o	η_2^o
PXST4-05	16.9	2.21	-2.12	0.02	1.35	-76	-81
PXST4-07	16.1	1.25	. 2.51	0.76	-0.38	47	49
PXST4-09	16.2	1.32	-3.86	-0.52	1.57	-89	-83
PXST4-11	15.9	2.60	0.0	0.52	0.78	-60	-63
PXST4-13	17.4	0.0	-5.79	-1.23	1.84	-68	-77
PXST4-19	16.5	2.15	2.72	1.00	-0.18	21	22
PXST4-23	17.2	2.27	-2.01	0.06	1.35	-69	-68
PXST4-39	18.1	2.29	2.54	1.05	-0.08	0	0
PXST4-41	17.4	1.43	-1.62	-0.04	0.97	-68	-69

Fatigue tests were carried out with the same proportions between both loading forces as those of monotonic, with stress ranges slightly below the critical ones. There were no differences found in fracture crack paths for brittle and fatigue tests, as far as the proportions between the loading forces in both perpendicular directions remained unchanged.

In the case of fatigue damage process, during a certain cycle there appeared, in a random way, small semi-elliptic non-propagating surface cracks that started from many points along the notch front. After a certain number of cycles, instantly appeared one bigger crack and started to propagate with increased rate. This phenomenon may be interpreted as the end of the initiating process. It is shown schematically in Fig. 5.

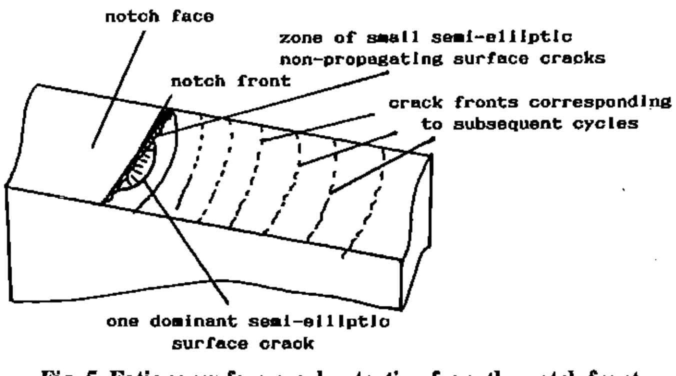

Fig. 5. Fatigue surface cracks starting from the notch front

Conclusions

Presented results of some tests on plexiglass cruciform specimens have shown that brittle properties of the material do not eliminate the possibility of carry out investigation concerned with fatigue, however the range between the threshold and critical stress intensity factors is very narrow and a special attention is needed during experiment.

There were no difference found in fracture crack paths for brittle and fatigue tests, resulted from the monotonic and cycling loading conditions, as far as the proportions between the forces in both perpendicular directions remained unchanged.

In the case of fatigue damage process, an initiation period may be defined as the number of cycles after which random small semi-elliptical and non-propagating cracks at the notch root change into one bigger crack that starts to propagate with significant rate corresponding to each loading cycle.

Brittle fracture resulted from the monotonic load appears usually in two steps, clearly registered during the tests. The first consists in forming one semi-elliptic crack, starting from the notch root, with its major axis equal to the specimen width. During this pre-cracking the load significantly drops and after increasing to approximately the same value - the second global fracture appears. Pre-cracking is probably due to the fact that stress fields (or damage conditions) along the straight line of the notch front are not the same and must be equalised. The surface of this first crack is not plane but in wave-form, showing longitudinal grooves. This suggests multiaxial damage process, i.e. the modes I and III appear in the same time along the crack front.

- For the slant notch, uniaxial forces produce unequal values of K_I and K_{II}, which are in different proportions than loading forces.
- Strong longitudinal compression decreased the value of K_{IC}, probably due to the non-singular term of the stress field.
- Strong compression perpendicular to the notch faces increased significantly critical stress intensity factor K_{II}.

In many cases the shape of specimens used in experiments may significantly change the effects of applied loads. For the cruciform specimens with a central notch along the specimen arms, longitudinal compressive forces produce positive value of K_I equal to 21% of the same tensile load acting in perpendicular direction. This fact can strongly change interpretation of the results. In such cases, numerical modelling of specimens and loading conditions is necessary.

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