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THE BOLTED JOINT STRENGTH AND FAILURE MODES IN FIBER COMPOSITES

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Abstract

A theoretical and experimental study of the strength of joints in laminated carbon and glass fiber reinforced plastic plates bolted to a steel fitting was conducted. It is well known that the failure mode of a bolt loaded joint in tension can have four failure modes : bearing failure, shearing out, net shear and net tension failure.
Different types of composite specimens, obtained by designing the joint with different edge-to-hole distance, were compared in order to determine the failure mode. The theoretical approach was carried out using two-dimensional analysis. Despite through-thickness stresses being ignored, some correspondance has been demonstrated between theoretical and experimental results.

I. Introduction

Low weight and high strength make carbon and glass fiber reinforced plastic a particularly interesting material for the aircraft industry. The anisotropy of the material has so far limited its application, as difficulty arises when joining the composites both to itself or to other materials [1].
Bolted joints represent an attractive method of attachment for composite materials but the effects on failure predictions of substantial combined stresses and mixed mode fracture are not yet thoroughly known. This is due to the fact that the 'hole size effect' is more pronounced for materials of significant orthotropy and composed of relatively brittle matrices. In addition most composites have low in-plane shear strength which is detrimental to mechanical fastening. Edge effects at holes or other discontinuities not only can cause local interlaminar failure, but the effective stress concentration factors can range from below to well above those occurring in a similar metal piece, depending primarily on laminate's fiber orientation with respect to load direction [2].
It is well known that the failure mode of composite specimens with open holes subjected to far-field tensile load is usually tension failure at the net section whereas the failure modes of bolt loaded joint in tension can have four modes : bearing, shearing out, net shear and net tension failure.
Net shear and shearing out failure in bolted joints can generally be avoided by choosing correctly the ratios e/d and w/d.
In order to determine the failure mode of composite laminated subjected to bolt load, some experimental tests and a theoretical approach was carried out.
The tensile strength test program includes specimens with and without hole, with loaded and unloaded holes for laminates with a different number of layers.
Stress distribution around a circular hole subjected to sinusoidal law bolt-load for finite-width plate was determinated via numerical method by using finite element stress analysis computer program.

II. Experimental plan

The tensile strength test program for glass-epoxy and graphite-epoxy at room temperature condition includes laminates with and without hole, with far-field tensile load and bolt loaded joints.
Specimens of 15x150 mm were cut from flat plates fabricated from four, eight and sixteen layers of prepreg by pressing it in a heated, matched-die mould.
The prepreg used was R-glass fiber and COURTAULDS E/HM-S-fiber with CIBA-GEIGY epoxy resin : the characteristics are shown in Table 1.

CHARACTERISTICS	CARBON FIBER	GLASS FIBER
FIBER TYPE	COURTAULDS E/HM-S	R-GLASS
FIBER DENSITY (KG/m3)	1860	2500
RESIN TYPE	920	920
RESIN DENSITY (KG/m3)	1260	1260
RESIN CONTENT (wt)	42%	33%
NOMINAL PLY THICKNESS (mm)	0.1555	0.175

TABLE 1 - FIBER AND RESIN CHARACTERISTICS

The data relative to unidirectional lamina for glass and carbon fiber are reported in Table 2.

UNIDIRECTIONAL LAMINA	E11 [GPa]	E22 [GPa]	E11/E22
GLASS	39.	7.8	5.011
CARBON	160.	5.7	27.960

TABLE 2 - LAMINA YOUNG MODULUS

For each fiber type there are three different symmetric laminate constructions : [0/90/90/0], [0/90/90/0]x2, [0/90/90/0]x4, as indicated in Table 3.

SPECIMENS	FIBER TYPE	NUMBER OF LAYERS	AV.THICKNESS (mm)
V1	GLASS	4	0.82
V2		8	1.70
V4		16	3.20
C1	CARBON	4	0.73
C2		8	1.46
C4		16	3.07

TABLE 3 - SPECIMENS GEOMETRIC CHARACTERISTICS

Drilled and reamed holes, of same diameter d = 4mm were positioned to give the various joint geometries. The width, w,was the same for all specimens (w/d = 3.75) and the edge-to-hole distance, e, was chosen (e/d = 2 ÷ 6) in an attempt to observe the different initial and final types of failure. The specimens were bolted to ensure that the load, which was applied symmetrically with respect to the pattern of holes, should act on the mid-line of the thickness. All tests were carried out by a testing machine of 50 KN capacity at a crosshead speed of 0.5 mm/min.
At least three specimens were tested for each geometrical configuration.

III. Experimental results

Three types of analyses were carried out. The first set was accomplished in order to evaluate the ultimate strength of the specimens used. The specimens without holes were clamped into grips with serrated-jaw type end connections and aligned by universal joints.
The results are summarized in Table 4.

SPECIMENS	YOUNG MODULUS [GPa]		ULT.STRENGTH [GPa]			
	EXPER.	THEOR.	EXPER.		THEOR.	
			INIT.	FIN.	INIT.	FIN.
V1	27	24	.56	.75	.46	.75
V2	27	24	.43	.78	.46	.75
V4	27	24	.45	.71	.46	.75
C1	75	83	.57	.57	.60	.60
C2	75	83	.58	.58	.60	.60
C4	75	83	.58	.58	.60	.60

TABLE 4 - CHARACTERISTICS FOR SPECIMENS WITHOUT HOLES

Theoretical values were obtained for comparison using a computer program made at Aerospace Department of Rome [3]. For the ultimate load, both for theoretical and experimental data, two values, indicated as 'initial' and 'final', are reported. The value 'initial' refers to the load at which failure on the first lamina appears; the other indicates the complete failure of the specimen.
It is important to note that, in carbon, the above said values are the same, whereas in glass, they are quite different. As a matter of fact, the E11/E22 ratio, for specimens tested, is higher in carbon than in glass lamina [Table 2].
This different characteristic causes two different modes of failure for glass and carbon laminate, as indicated in Fig.1.

As to carbon laminate, tension failure on net crosshead section is observed; as to glass laminate, the failure starts at different points of fiber. This phenomenon is more pronounced as the specimen thickness decreases.

A second set of analyses was selected to investigate the effects of a circular cutout on strength of composite specimens, subjected to far-field tensile load. The failure mode observed was tension failure at the net section as shown in Fig.2, and the"final loads" are reported in Table 5.

SPECIMENS	ULT. LOAD [GPa]	SPECIMENS	ULT. LOAD [GPa]
V1	0.69	C1	0.46
V2	0.56	C2	0.38
V4	0.54	C4	0.34

TABLE 5 - SPECIMENS SUBJECTED TO FAR-FIELD TENSILE LOAD

It seems that the reduction of ultimate strenght as the number of layers increases, is due to growing effects of interlaminar stress.

A third set of analyses was selected to point out the progress of each joint failure at different values of e/d ratio for bolt loaded joints.

Typical load-displacement qualitative diagrams are shown in Fig.3 for different values of e/d and the progress of each joint failure is shown in the same figure.

For small values of e/d, cracks were first observed at A and B, followed shortly by cracks at C. The cracks cause discontinuities in form of a step in the load curve. The cracks at A and B grew towards each other as load increases. Ultimate failure was by shear out.

In the range $2.5 < e/d < 5.0$, discontinuities of load-displacement plot, took the form of a distinct change of slope. Simultaneous initial cracks at A and B were observed. These cracks gradually joined, and after the crack at C, the ultimate failure was primarily in a shear out mode on a wider zone of the specimens. For large values of e/d, simultaneous initial cracking was observed at A, B and C with ultimate failure as tension through hole.

Pictures of failed specimens are shown in Fig.4 for glass and Fig.5 for carbon specimens.

Whilst ultimate failure was again either tensile or shear out, there was always evidence of bearing failure.

In view of the difficulty in determining the load at which bearing failure occurs, only the maximum load will be used here as a measure of joint strength.

The maximum load at which the failure occurs in each type of joint are compared in Fig.6 and 7, respectively for glass and carbon fibers.

The ultimate load for bolt loaded, are considerably lower than far-field load, due to the higher stress concentration around the hole. The ultimate load increases with specimen thickness.

IV. Theoretical approach

Stress and strength predictions for composite laminates with a circular cutout are important in a study aimed at understanding the characteristics of a crack growth during failure.

Stress distribution around a circular hole subjected to sinusoidally distributed radial bolt-load in an infinite plate with homogeneous anisotropic properties, may be calculated from Waszezak's solution [4].

For finite-width plates, solutions are also available either via complex approach [5], or via numerical method, such as the finite element approach [6],[7].

Stresses around circular holes are obtained here by using NASTRAN computer program.

Experimental results [8] and theoretical stress [9] investigations indicate that the interlaminar normal stress is a factor to initiate delamination; then it is necessary to undertake a three-dimensional analysis.

It is known however [10] that when the laminate is constrained transversally, as by washers in bolt-loaded holes, the three dimensional effect can be neglected.

In the present paper two-dimensional plane stress elements are used to represent an homogeneous orthotropic material for the purposes of stiffness calculation.

A typical network for joint is shown in Fig.8.

The bulk data deck for NASTRAN program is automatically generated by an ad hoc program when the following parameters are given: w, e, d, and the number of elements.

The arrangement and number of elements was altered according to the particular situation under investigation.

The load applied by the pin was represented as sinusoidal distribution on the element nodes at the top half of the hole boundary, the vertical resultant being a force of 2.5 kN.
The bulk of the work undertaken investigated the effect of changing the end distance of a single-hole joint.
The material properties used in the stress analysis are given in Table 6.

YOUNG MODULUS [GPa] E11 = E22	POISSON RATIO v12 = v21	SHEAR MODULUS [GPa] G12
83.11	0.022	3.09

TABLE 6 - INPUT DATA FOR NASTRAN PROGRAM

The geometrical parameters used are $w/d = 3.75$ and $e/d = 2 \div 6$.
Fig.9 shows a typical diagram of stress distribution around the holes ($\theta = 0 \div \pi$).
It was seen that the maximum tensile load in the fiber direction grows as e/d increases. The maximum compressive load was seen to change little with e/d.
These variations in load can be related to the failure mode that becomes closer and closer to net tension, as e/d increases.

V. Conclusions

The two-dimensional theoretical study must be seen as an attempt to well understand physical phenomena, but this information alone does not explain completely the failure modes occurring at different e/d ratios.
The precise nature of failure mode depends critically on many parameters, such as stacking sequence, fiber type, dimension, ...
A more realistic schematization requires a three-dimensional analysis and more confidence with composite materials.

References

[1] BROUTMAN L.J.,KROCK R.H. - Editors
'Structural Design and Analysis' - COMPOSITE MATERIALS - Vol.8
[2] HARRIS A.,ORRINGER O.
'Investigation of Angle-Ply Delamination Specimen for Interlaminar Strength test. - J. Composite Materials - Vol.12 (1978)
[3] BARBONI R.,PERONI I.
'Mechanical and Thermal Coefficients in Composite Materials' - Q.C.E. 23 - Scuola di Ingegneria Aerospaziale - Roma (1979)
[4] WASZEZAK J.P.
'A Synthesis Procedure for Mechanically Fastened Joints in Advanced Composite Materials' - Report SM-73-11 - Carnegie-Mellon University - Pittsburgh (1973)
[5] OGNOWSKY J.M.
'Analytical Study of Finite Geometry Plates with Stress Concentrations'
AIAA/ASME 21st SDM Conference (1980)
[6] DE JONG T.
'Stresses around Pin-loaded Holes in Elastically Orthotropic or Isotropic Plates' - J. Composite Materials Vol.11 (1977)
[7] WONG C.M.S.,MATTHEWS F.L.
'A Finite Element Analysis of Single and Two-Hole Bolted Joints in Fibre Reinforced Plastic' - J. Composite Materials Vol.15 (1981)
[8] PIPES R.B.,KAMINSKI B.E.,PAGANO N.J.
'Influence of Free Edge upon the Strength of Angle-Ply Laminates'
ASTMS-P520
[9] RYBICKI E.F.,SCHMESSER D.W.
'Effect of Stacking Sequence and Lay-up Angle on Free Edge Stresses around a Hole in Laminated Plate under Tension' - J. Composite Materials (1978)
[10] STOCKDALE J.H.,MATTHEWS F.L.
'The Effect of Clamping Pressure on Bolt Bearing Load in Glass Fibre Reinforced Plastics' - Composites Vol.7 (1976)

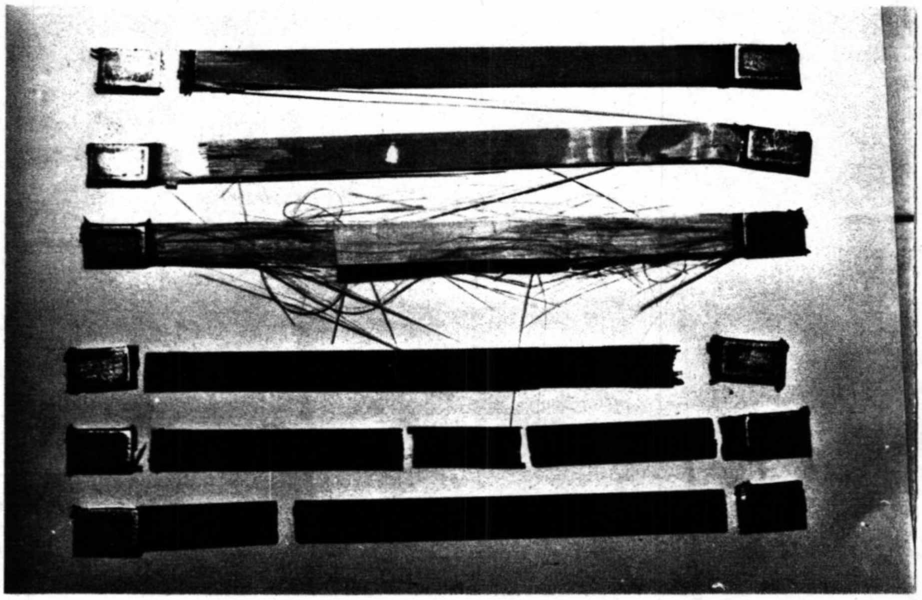


Fig. 1

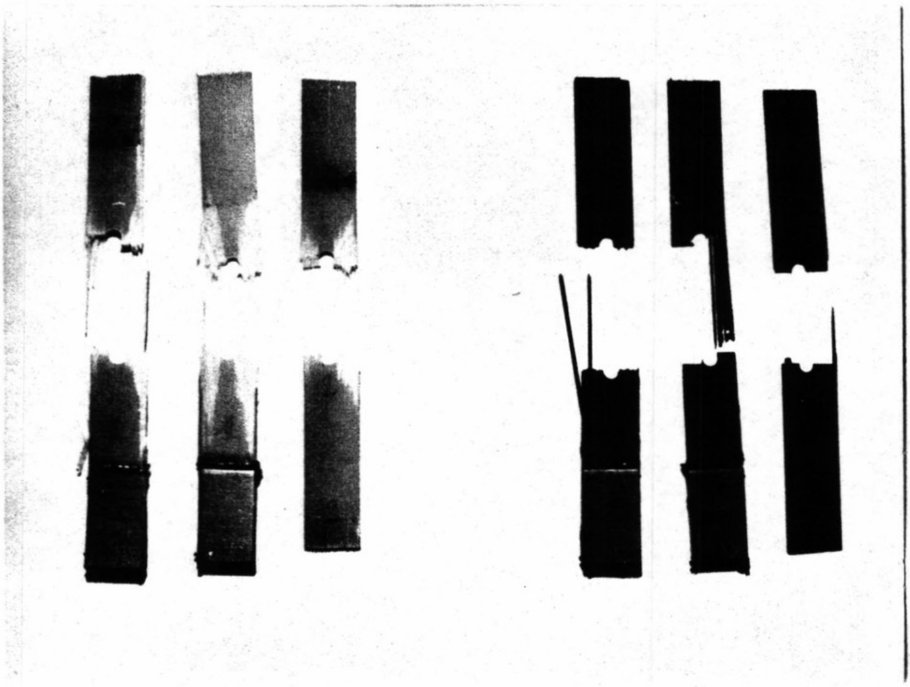
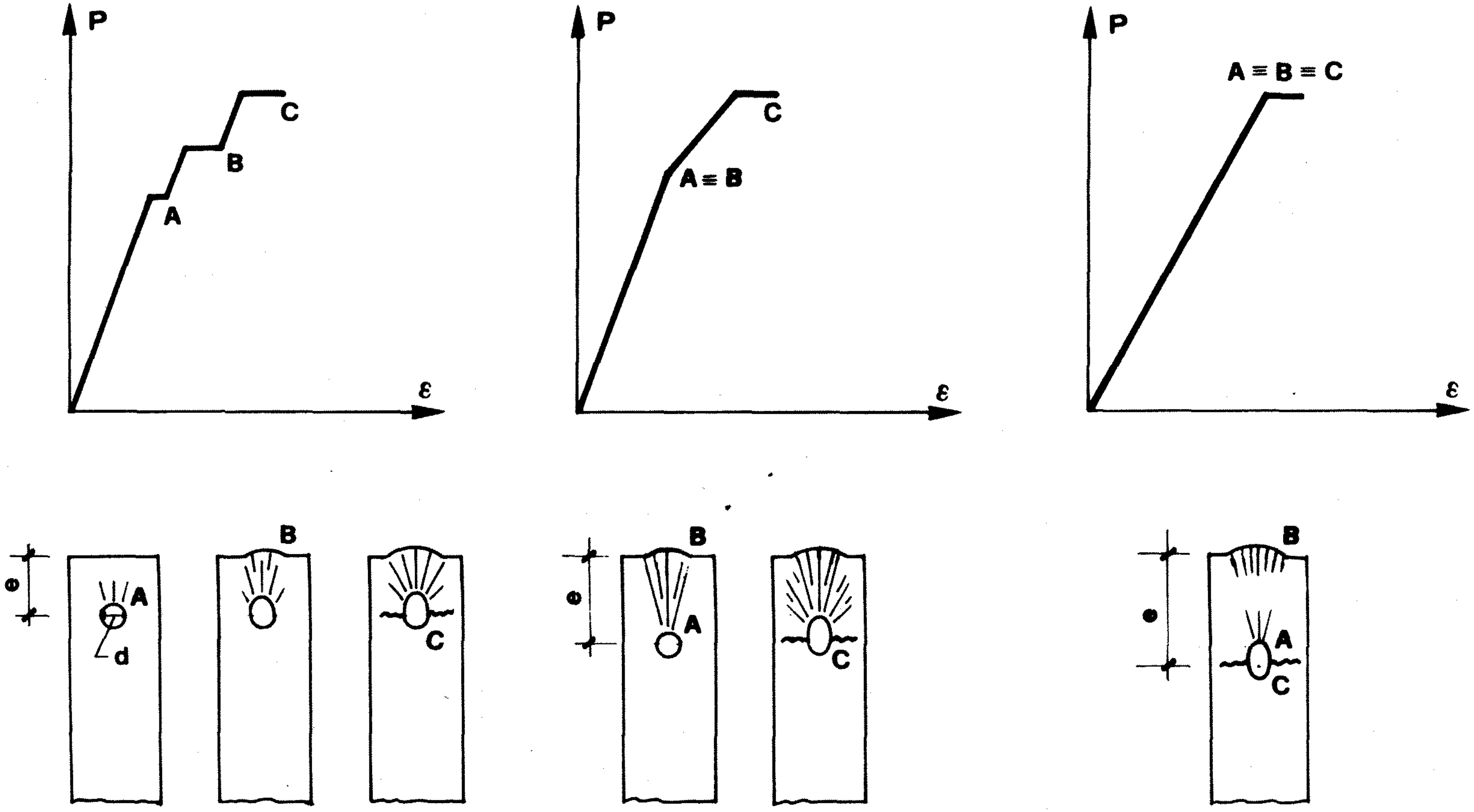


Fig. 2



$e/d < 2.5$ $2.5 < e/d < 5.0$ $e/d > 5.0$

Fig. 3

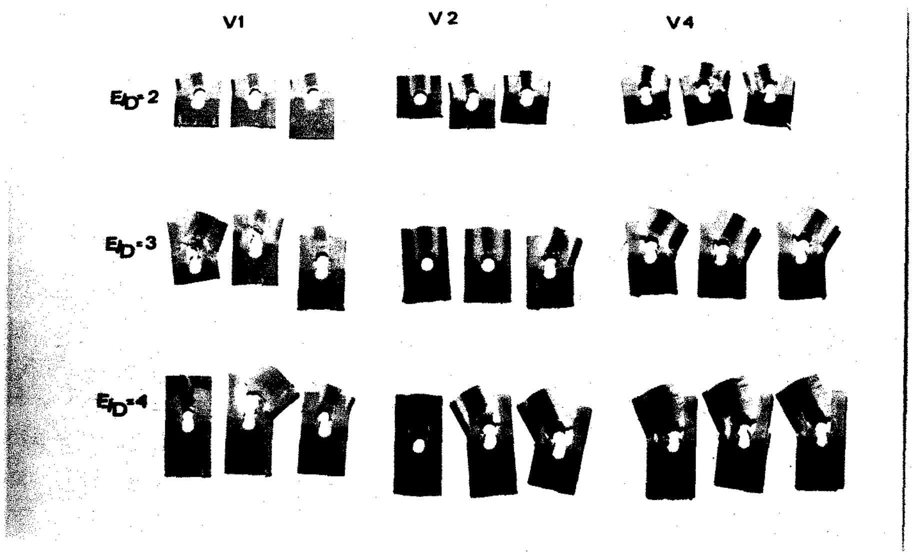


Fig. 4

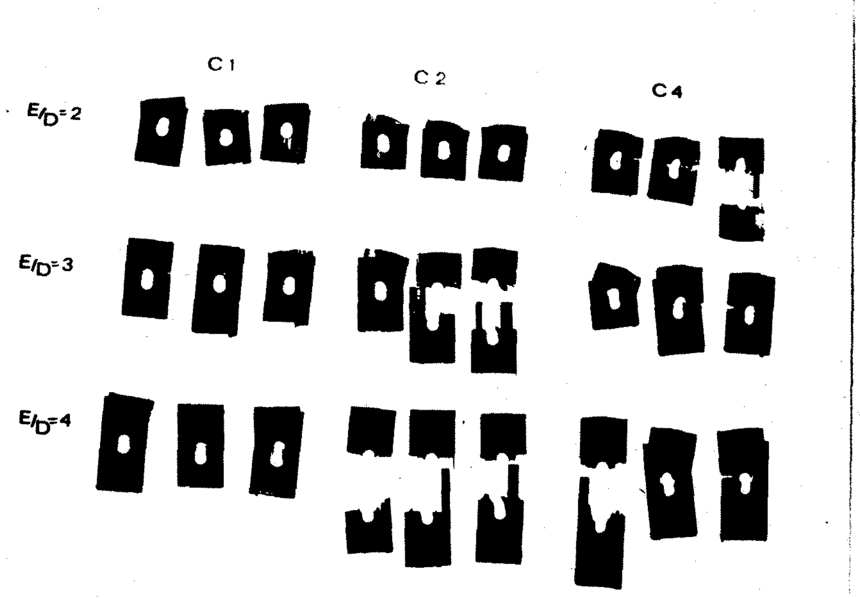


Fig. 5

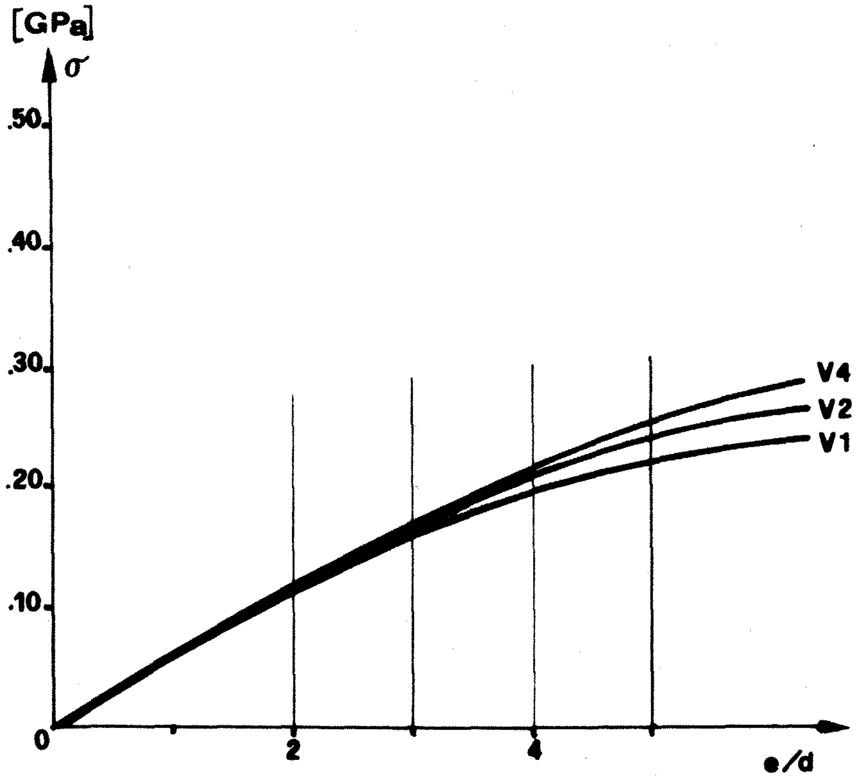

[GPa]
σ
.50
.40
.30
.20
.10
0
2
4
e/d
V4
V2
V1

Fig. 6

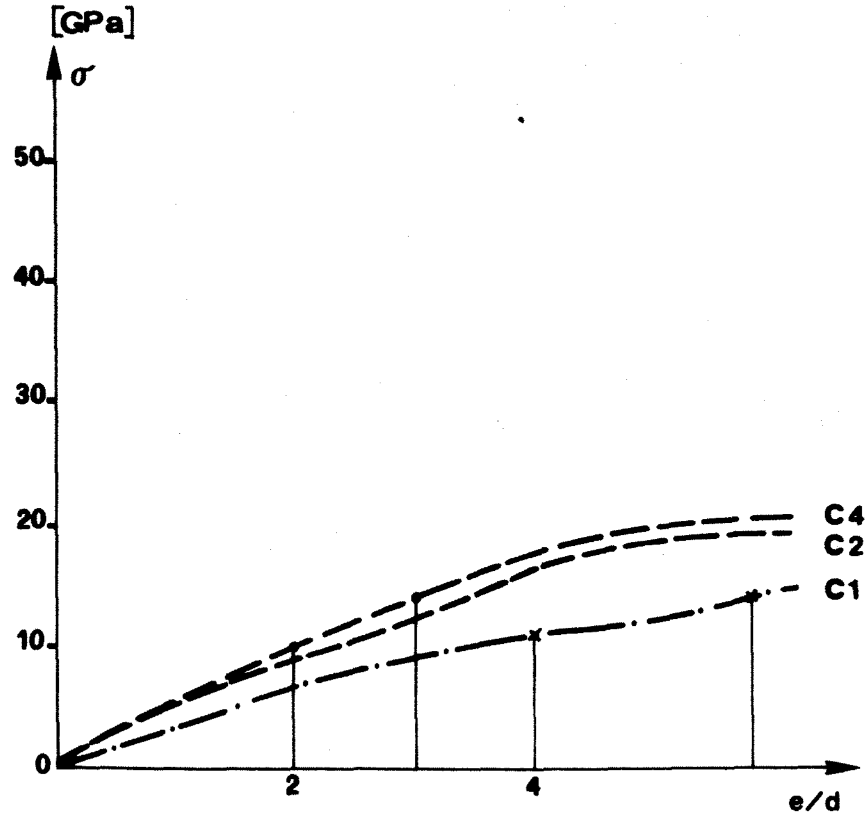

[GPa]
σ
50
40
30
20
10
0
2
4
e/d
C4
C2
C1

Fig. 7

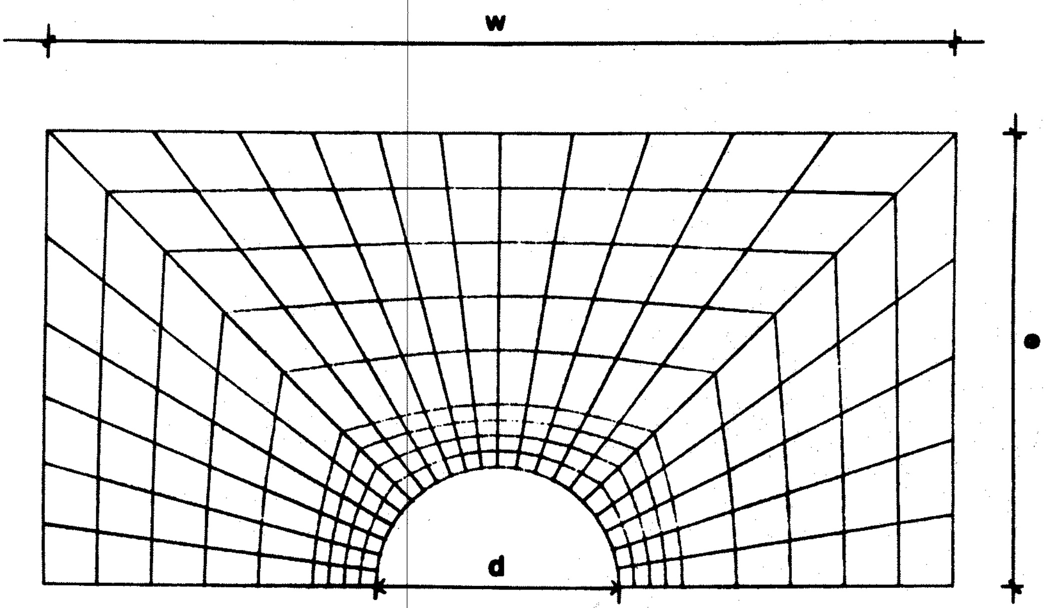


Fig. 8

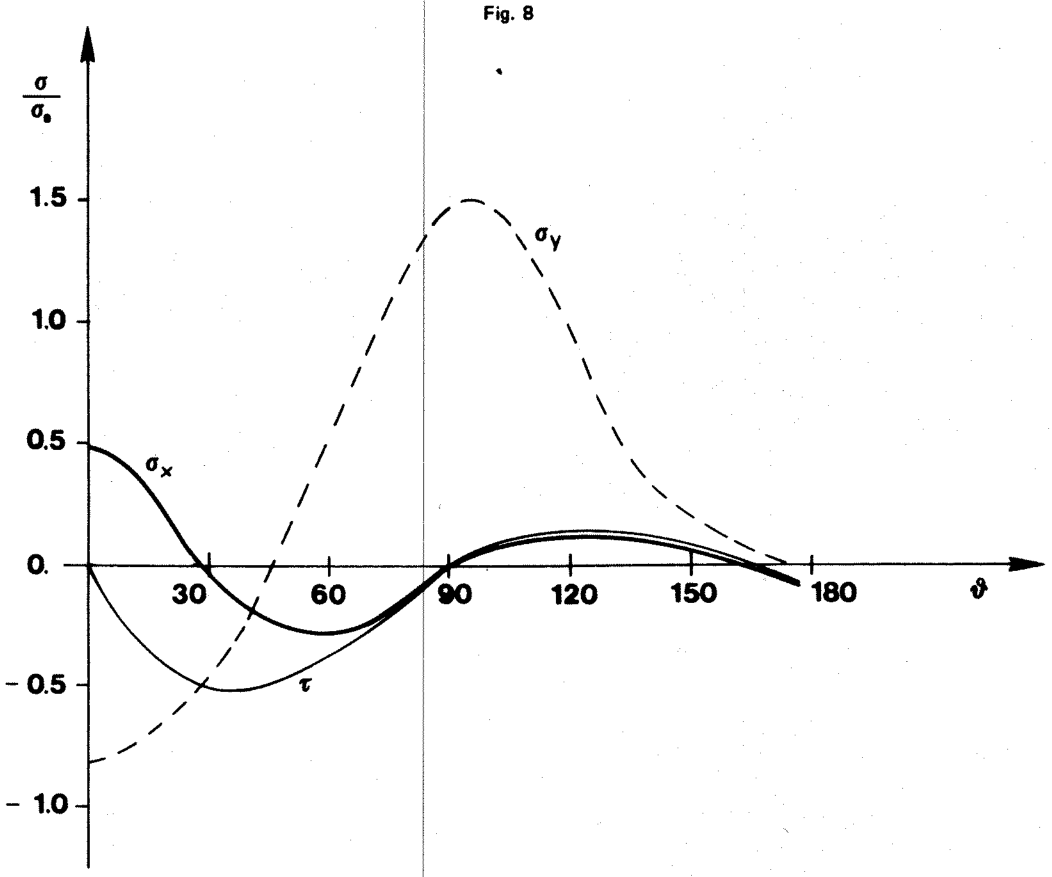


Fig. 9

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