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EXPERIMENTAL BEHAVIOR OF GRAPHITE/EPOXY PANELS WITH CUT-OUTS UNDER BIAXIAL TENSION, COMPRESSION AND SHEAR LOADS

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Abstract

The behaviour of graphite/epoxy panels with rectangular cutouts subjected to uniaxial and combined biaxial tension and shear loadings has been investigated. The testing machine, already manufactured for biaxial compression and shear loads, has been infact modified making possible to apply, also in the longitudinal direction, a tension load up to 400 kN. The strain distribution has been recorded in several points of a composite panel, due to the presence of the rectangular cutout, in order to hemphasize the effect of stress concentrations. The strain distribution around an oval cutout, very close to the rectangular opening, of an infinite anisotropic plate has been derived by the Lekhnitskii's theory obtaining a good agreement, in several cases, with the experimental results. Under uniaxial load, a very high strain concentration has been measured in the transverse direction along the cutout end; the introduction of the transverse and shear load, greatly reduce the longitudinal and transverse strain level along both sides and ends of the cutout; indeed, a very high strain level has been recorded in the cutout corner, at 45 degree of direction, when the three loads are applied simultaneously. A FEM analysis has also been carried out for the uniaxial test, obtaining a good agreement with the experimental results.

Introduction

Advanced composites panels with holes or rectangular cutouts have wide application in aerospace structural components, making access doors to systems or reducing weight of components moderately loaded.

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Several papers are available in the literature on the buckling and postbuckling behavior of unstiffened and stiffened composite panels with circular holes or rectangular cutouts [(1)]. A previous author's investigation[(2)] concerned the experimental behaviour of a graphite/epoxy panel with rectangular cutouts subjected to uniaxial compression, biaxial compression and combined biaxial compression and shear loads, also in the post-buckling field, obtaining thousands of strain results. From the comparison of the results between the panel tested with and without cutouts, it has been noted that uniaxial and biaxial tests showed a little reduction in the buckling load with increasing cutout-to-width ratio; biaxial compression and shear loading test showed a wider reduction of the critical load and an higher values of the out of plane deflection. The buckling mode doesn't seem to be modified by the presence of the cutouts; under uniaxial compression, the mode deflection changed from one to two half-waves at high postbuckling load level, in presence of the hole. Longitudinal membrane strains are reduced in proximity of the cutout edge in the postbuckling regime for all loading cases; indeed, a very high surface strain was measured.

The stress-strain distribution around elliptic cutout of an infinite anisotropic plate was derived by Lekhnitskii, in his famous book[(3)], who gave the theoretical resolution for most of the problems. With respect to an isotropic panel with circular hole subjected to uniaxial load, which denotes a stress concentration factor of 3 in most geometric conditions, local stress around holes or cutouts of anisotropic panels can be more pronounced in function of anisotropy, loading direction and hole shape; a stress concentration factor (SCF) up to 7-8 should be possible in some cases, producing a failure at a lower applied load. Many theoretical and experimental results are available in the very exhaustive book written

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by Tan[4]; the results regards orthotropic and anisotropic panels with circular or elliptical cutout subjected mainly to uniaxial load and in few cases to biaxial or shear loadings. However, no theoretical and experimental results were found in the open literature for panels with rectangular cutouts subjected simultaneously to combined biaxial tension and shear load. The aim of this report deals with the study of the strain distribution in a graphite/epoxy panel, due to the presence of the rectangular cutout, subjected to combined loads; an analytical approach has also been devoleped to compare with the experimental results, as well as a numerical analysis by the MSC/PATRAN/NASTRAN FEM Code.

Theoretical analysis

The stress distribution around elliptic cutout of an infinite anisotropic plate under uniaxial load[3] was derived using a complex variable method, by superposing an opening field to a uniform field. Within the CLT hypothesis, the constitutive equation of a symmetric laminate can be expressed by introducing the Airy function, which satisfy the equilibrium equations, and the compatibility equation; by solving out the latter, as function of the stress function, and by using four linear differential operators, the principal solutions of the characteristic equation are the complex roots μ_1, μ_2; finally, has been calculate the normal stress for an element tangential to the opening. Starting from this analysis, stresses around circular holes or square cutout with round corners have also been evaluated. The cutout of the tested panel has been simulated as an elliptic opening with proper coefficient c and ϵ in the geometric relations:

$x = a(cos\theta + \epsilon cos3\theta) \qquad y = a(csin\theta - \epsilon sin3\theta)$

By choosing c=0.685 and $\epsilon = -1/12$, the cutout will have straight long sides and ends slightly round; the effective ratio between the two sides of the cutout has been maintained.

Within these hypotheses, the normal stress component N_θ in any point of the cutout of an orthotropic panel under uniaxial tension load (N_x) is given by:

$$SCF = N_\theta/N_x = B^2/C^2 + (1/LC^2)\{c(AD^4cos\theta + BC^4nsin\theta) + \epsilon[2AC^4cknb^*_{11}cos\theta - 3AD^4cos3\theta - BC^4n(2a^*_{11}csin\theta + 3sin3\theta)] + 2\epsilon^2C^4cn[-Ak*(b^*_{21}cos\theta + 3b^*_{23}cos3\theta) + B(a^*_{21}sin\theta + 3a^*_{23}sin3\theta)]\} \qquad (1)$$

where: k=-$\mu_1 * \mu_2$ and n=-i($\mu_1 + \mu_2$); A, B, C, D, L are function of the complex roots. A similar expression has been obtained when the uniaxial load is applied in the y-direction. The stress concentration factor has than been calculated in several point of the cutout under uniaxial load as well as under biaxial load (assuming applicable the superposition of both stress distribution).

A finite-width correction factor[4] (FWC) has to multiply the infinite plate solution to obtain the maximum stress concentration at the opening edge of a finite-plate; the analytical solution has been reported by Tan for circular holes or elliptical cutout. In most of the cases reported, an higher SCF has to be put into account; for geometric dimensions and lay-up of the panel herein reported, the FWC has not yet been obtained; for circular or elliptical cutout, similar to the panel herein tested, a value about 10-15% higher than the infinite plate solution[4] has been determinate.

Experimental results

A new testing machine has been conceived in order to simultaneously apply combined biaxial tension, compression and shear loads[5,6], and built by the Italian company "AIP Studio". A maximum longitudinal load of 520 kN in compression and 400 kN in tension, a transverse compression or tension load of 200 kN and a positive or negative shear load of 200 kN can be applied to panels with dimensions lower than 1000 by 700 mm (Fig.1). Longitudinal load is applied by two independently controlled servo-actuators; the transverse load application system, which is made up of two independently controlled servo-actuators, floats in order not to interfere with the longitudinal and shear loads. Shear load is applied to the bottom end of the panel by a servo-actuator. The test rig is completely loop-controlled via electronic modules which are closed by 9 transducers; however, since the five servo-actuators may be controlled separately, the test rig can apply different load configurations than those reported above. The machine can operate both in load or displacement control.

Many experimental tests have been made using a specimen BS1. The panel was manufactured using graphite/epoxy material (pre-preg T300/985 Cycom), vacuum bagged and autoclave cured. Material properties used in the analysis were experimentally determined to be: $E_1 = 124.0GPa$; $\nu_{12} = 0.30$ $E_2 = 8.3GPa$; $G_{12} = 5.60GPa$.

The panel lay-up is: $(45/0_4/-45/90)_{3s}$ with a thickness of 8.726mm; it was bolted to the machine by stiff steel L-profiles; the effective panel length and width are 920mm and 620mm, taken between the bolt line; rectangular cutout was machined up to 304 mm long and 200 mm wide, having a radius at corner of 25 mm, corresponding to a fictitius d/W=0.33.

The tension loading case only (in various combination) will be reported in this report, since the compression loading results have been previously presented(2). The comparisons between various loading cases, both tension and compression, are considered at the end of this paper in order to investigate the effect of loading on strain distribution. Many tests, however, have been made and a lot of results have been recorded. 50 back-to-back strain gauges (sg) were bonded to the panel in order to investigate the strain distribution; the distance between the edge of cutout and the center of back-to-back gauges 21-22, 19-20, 43, 9-10, 17-18 and 49-50 are (Fig. 1): 10, 60, 125, 21, 13 and 13 mm; sg 23-24 and 25-26 are symmetric to 21-22 and 19-20 with respect to the cutout center. The strain gauges 49-50 are positioned at the rigth hand corner of the cutout in a 45 degree direction with respect to the longitudinal direction of the panel; they are strain gauges of strain rosettes n. 5-6 in order to measure the local shear strain. Strain gauge dimensions (3mm by 10mm) are very important in evaluate the SCF, since the strain measured is an average value along the gauge active area; a nonlinear measurement should be possible at higher strain levels. 10 inductive transducers (TR) were used for recording the out-of-plane panel deflection in the compression loading case.

Test of uniaxial tension

The strain distribution around the cutout, in the uniaxial tensile tests are reported in Figure 2. A very low longitudinal strain (Fig. 2a) has been recorded in the top end of the cutout (sg 9-10), due to the fact that the load flows around the cutout, increasing the load on the lateral part of the panel. Longitudinal strains measured very close to the cutout lateral edge (sg 21-22) and trasverse strains measured very close to the top of the cutout end (sg 17-18), are reported in Figure 2c and 2b. These pictures show that the transverse strain in the top of the cutout is greater than longitudinal membrane strain, although a Poisson's ratio of 0.295 was calculated by the laminate theory; at the maximum applied load of 196.2 kN the transverse strain is 1.06 time the longitudinal strain of sg 21-22; furthermore it is 8.9 time greater than strain expected in that position in the case without the hole. This effect is mainly due to the presence of the cutout itself and to its deformation under load; it is worthy to note that the measured strain are no more linear for longitudinal load greater than 100 kN.

The longitudinal membrane strains in the middle section of the panel are collected in Figure 2d in order to hemphasize the cutout concentration effects; the load distribution is well behaved and is symmetric with respect to the longitudinal middle line; sg 43, positioned near to the panel side, is quite similar to the longitudinal strain of the unnothched laminate. Strains measured at 45 degree (sg 49-50) are reported in Figure 2e, and maximum shear strains, recorded by the strain rosette 5-6, are reported in Figure 2f; they show an high level of strain as effect of the corner.

Test of biaxial tension

The results of the biaxial tension test are reported in Figure 3; transverse load is 40% of the longitudinal load. It is worthy to note that, up to the same maximum longitudinal applied load of 200 kN, a sensible strain reduction has been recorded, unless shear strain; longitudinal strains (Fig.3c) near the lateral cutout edge (sg 21-22) resulted 35% lower than in uniaxial test; the transverse strain (Fig.3b) in the top edge (sg 17-18) is largely different from that measured in the uniaxial test with a strain reduction in value up to 90%.

The longitudinal membrane strains in the middle section of the panel are collected in Figure 3d in order to hemphasize the cutout concentration effects; the same strains have been measured between sg 19-20 and 23-24, in spite of their different distance from the cutout; sg 43, positioned near to the panel side, is quite similar to the longitudinal strain of the unnothched laminate; strain are, indeed, higher around the cutout corner because of the combination of the two loads. As it is clear from Figure 3e, strains measured by gauges placed at 45 degree have been 100% higher than in the uniaxial test (although lower shear strain have been recorded by rosette n. 5-6, Fig. 3f).

Test of biaxial tension and shear

The panel has been subjected to positive and negative shear load (50% the longitudinal load) in combination with transverse tension load (40% the longitudinal load) and the strain distribution is reported in Figure 4. The strain distribution is according to the shear loading direction revealing a general orientation along the diagonals of the panel. In both load combination, longitudinal strains (sg 9-10) as well as transverse strains (sg 17-18), measured close to the top of the cutout end, are substantially unloaded the former and slightly loaded the latter.

The longitudinal membrane strains in the middle section of the panel are collected in Figures 4a for a negative shear (maximum applid longitudinal load of 167 kN) and 4b for a positive shear (maximum applied longitudinal load of 118 kN); the load distribution is no more well behaved with respect to the longitudinal middle line, because of the shear deformation of the panel; different strains have been measured between sg 19 and 25 although were bonded at the same distance from the cutout. In this case, strain concentrations are more pronounced around the corner of the cutout because of the interation of the three loads. As it is clear from Figures 4c - 4e, strains measured by gauges placed at 45 degree, and 4d - 4f (shear strain measured by rosette n. 5-6) for negative and positive shear, respectively, the same deformations of the uniaxial test have been recorded although at much lower longitudinal loads.

Comparison between loading conditions

Observing strains behaviour, a general correspondence could exist between tension and compression loading cases. Regarding longitudinal strains at the cutout edge (sg 21-22, Fig. 5a-b) it can be said that the introduction of the transverse and shear loads greatly reduce the longitudinal strain level, both in tension as in compression. Higher reductions have also been obtained in the transverse strain level (sg 17-18). The introduction of the transverse and shear load, both positive and negative, altered significantly strains, with respect to the uniaxial load, at cutout corners, becoming a critical area of the panel; this behaviour is observed also in compression up to the critical buckling level. In that case the membrane strain is not increased at all and tends to reduce in the postbuckling range; as it is clear from sg 49-50 (Fig 5c-d), strains up to 4-5 times that of the uniaxial test can be measured, at 45 degree, as in compression as well in tension; maximum shear strains too (Fig. 5e-f) denote an always strain increase, although of less entity. It is also clear the effect of the direction of the shear that cause a change in sign for the strain.

Experimental and analytical comparison

A comparison has been made between experimental, analytical and numerical results.

Several analytical results have been obtained by the application of the Lekhnitskii's theory; although the rectangular cutout has been very well simulated from an oval cutout, by a proper use of geometric coefficient, a physical difference exist between the two cutouts; neverthless, by applying the analytical expression (1), the SCF has been calculated and reported in Figure 6; each result is divided by the unnotched theoretical stress; the experimental stresses have been first obtained, by using the laminate extensional stiffnesses, from strains measured along the cutout and than compared with the analytical values.

The longitudinal SCF obtained in the uniaxial test, are drawn in Figure 6a; the unnotched longitudinal strain (EPSx nocut), obtained by CLT, has been, first, compared with the experimental strain measured by sg 43 (43 exp); for low applied load, a lower strain have been measured with respect to the theorethical value, while a better agreement has been obtained for loads higher than 100 kN; the experimental strains measured by strain gauge 21 at the lateral edge of the cutout (21 exp), denote an SCF always incresing with the applied load (from 1.58 to 2.57); the analytical results obtained by eq. 1 have been reported (21 theory) and represented by a constant value of 1.8; it would, than, seem that there is no a correspondence, unless at low applied load, between theoretical and experimental results. However, from the many experimental results reported in his book[4], Tan suggested to draw a tangent line to the experimental stress-strain curve and to consider this line as reference value for measuring the strain concentration. If we should adopt this suggestion, the experimental SCF we obtain (21 exp linear) would be perfectly constant resulting slightly higher (1.98) the analytical value obtained by eq.1. Indeed, if a FWC of 10% should be enclosed a very good agreement is obtained between the analytical and experimental results.

Longitudinal and transverse strains obtained in the uniaxial test, are drown in Figure 6b and 6c; the unnotched longitudinal and transverse strain (EPSx nocut, EPSy nocut), obtained by CLT, has been, first, compared with the experimental strain measured by sg 43 and sg 17 (43 exp, 17 exp); it is very clear as the experimental transverse SCF resulted much higher than the theorethical value (up to 9 time at the highest load); the analytical results obtained by eq. 1 (17 theory) is represented by a constant value of -0.55; considering the tangent to the curve, the experimental SCF obtained (17 exp linear) would be higher (-0.82) than analytical value. Also considering a FWC of 10% a little difference would result between the analytical and experimental results; the difference being due to the oval shape of the cutout in the y-direction.

Longitudinal and transverse strains obtained in the biaxial tension test, are drawn in Figures 6d, e, f; a similar behaviour to the uniaxial test has been obtained, with a better agreement also for the transverse SCF.

A numerical analysis has also been carried out by using the MSC/PATRAN/NASTRAN Finite Element Code. The panel (Fig. 7a) has been modeled by 2700 elements, type CQUAD4; a Multi Point Constraint has been imposed to each side in order to have the same uniform displacement along the bolted length of the panel. A linear behaviour has been obtained up to the maximum applied load. Edge displacement, longitudinal and transverse strains of the uniaxial tension test, at an applied load of 117.7 kN, are represented in Figures 7b, 7c and 7d. SCFs of 2.05 and -0.75 have been obtained for strain gauges 21 and 17, respectively, resulting in a very good agreement with the experimental value. Further numerical tests are in progress for biaxial and shear loading.

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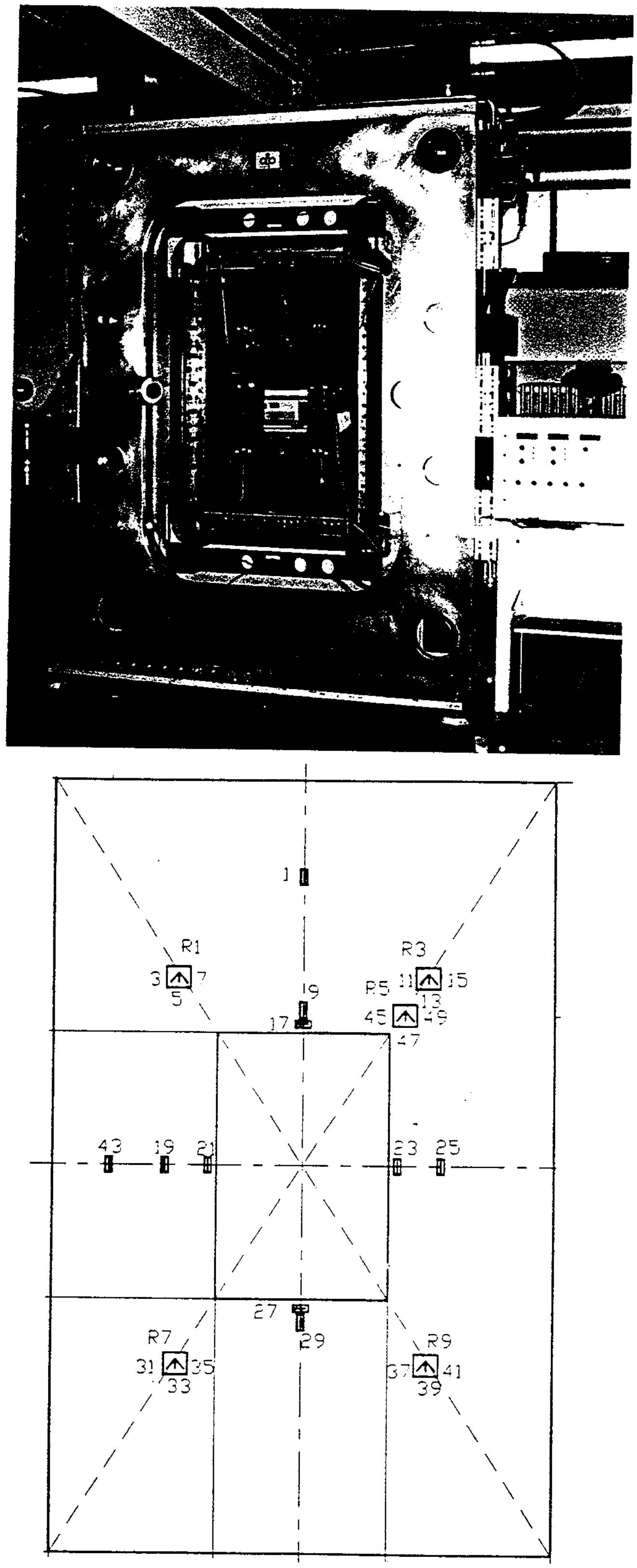

Fig.1- Testing machine for combined biaxial and shear loading (above). Strain gauges location (below).

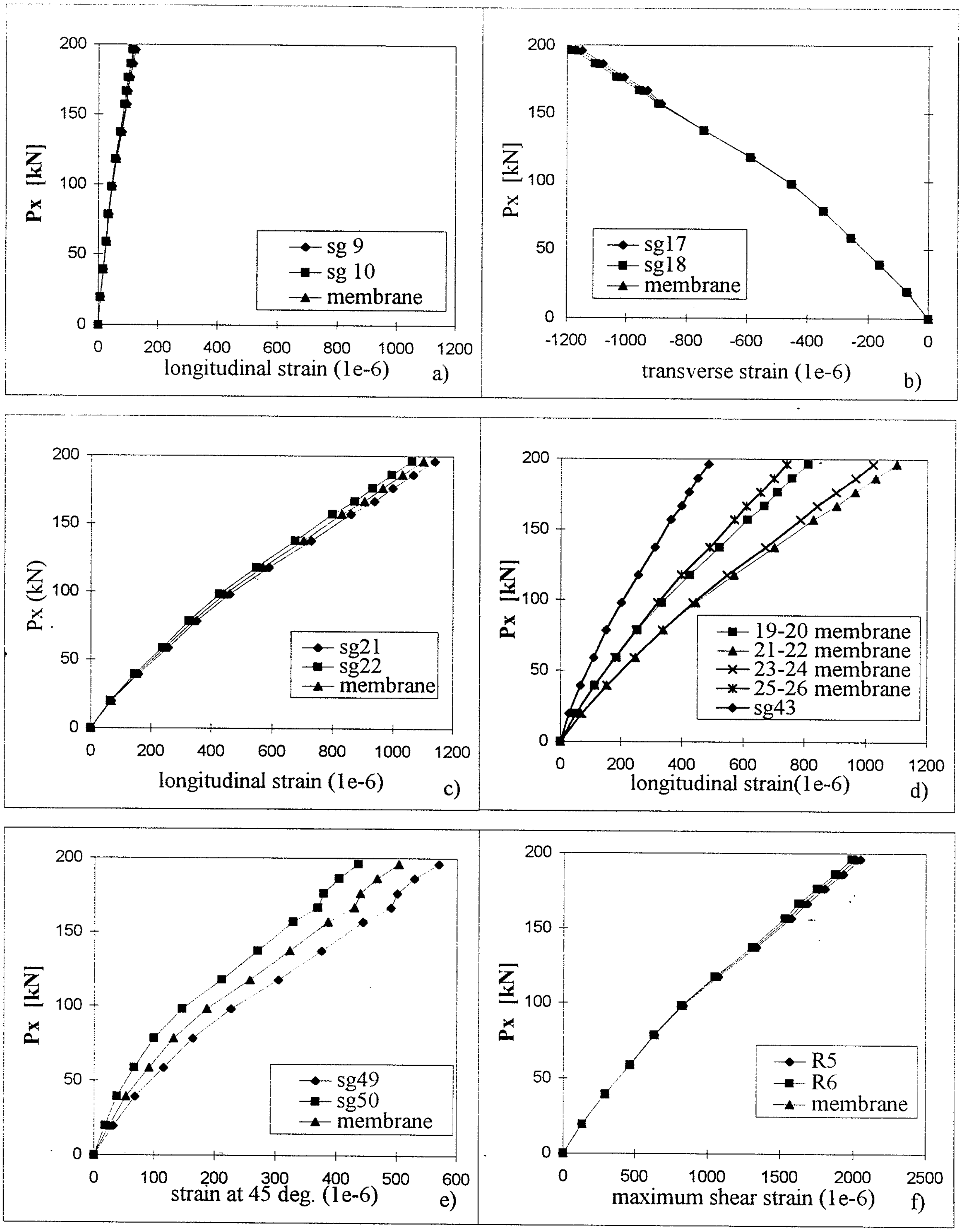

Fig.2 - Uniaxial tension test

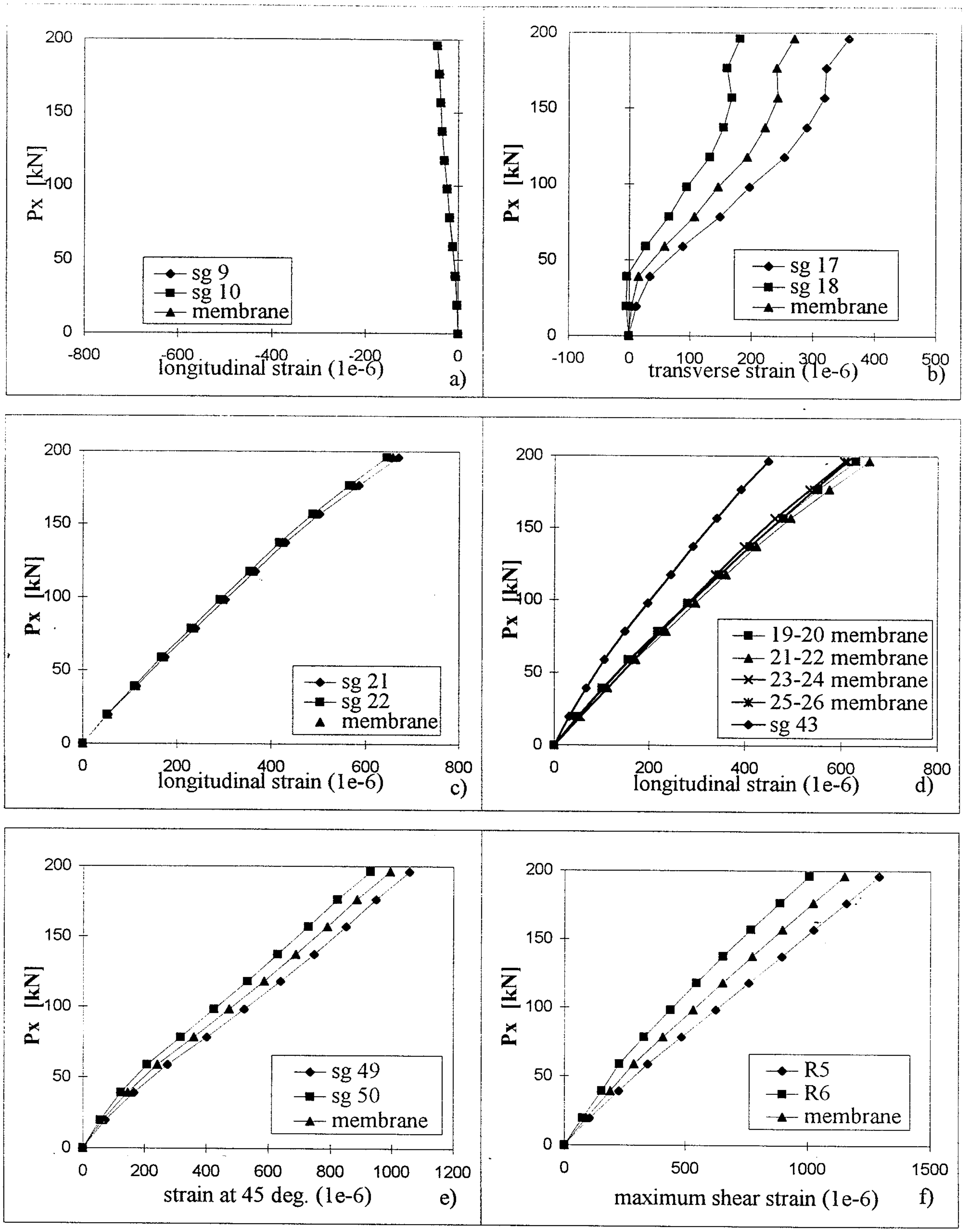

Fig.3 - Biaxial tension test

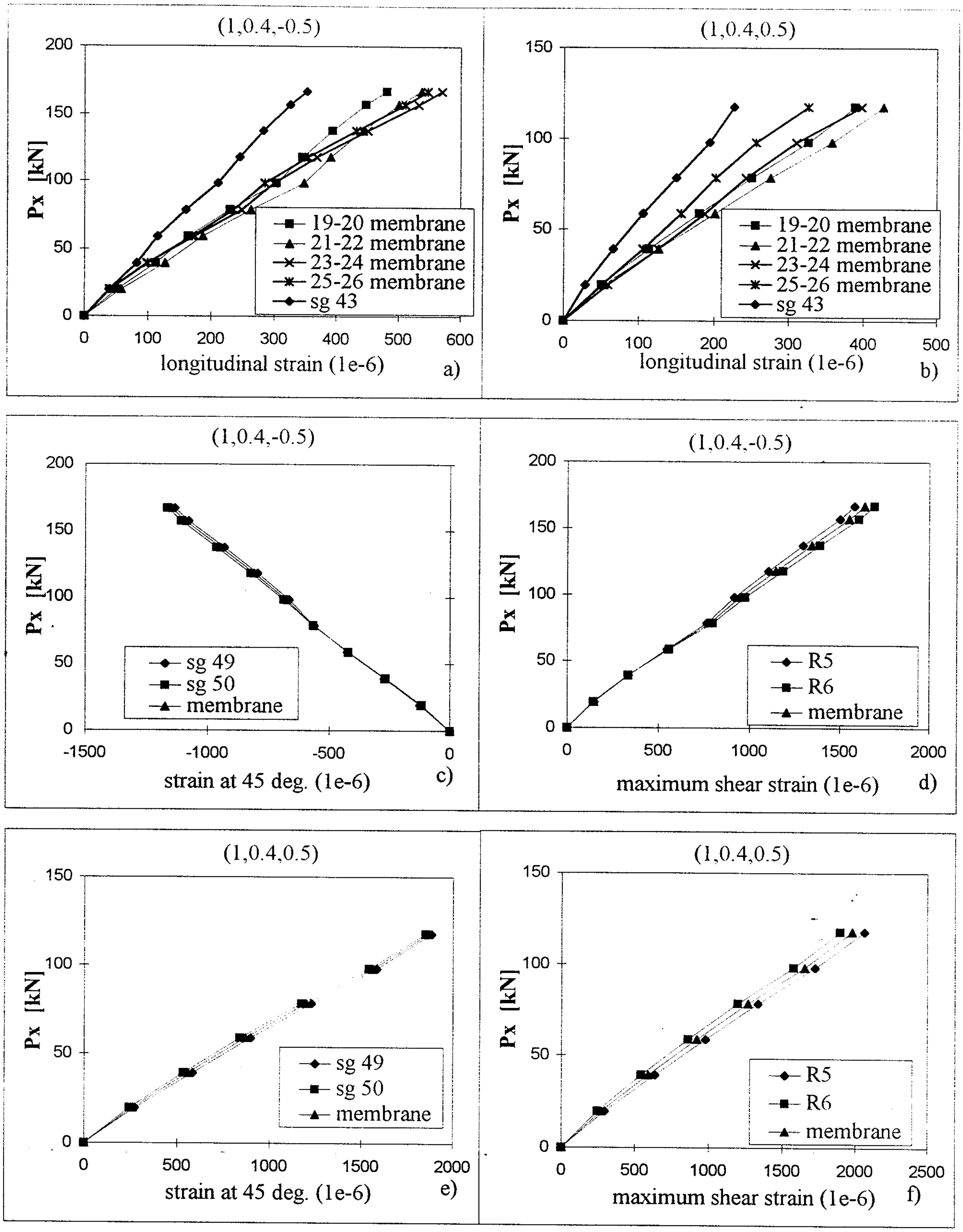

Fig.4 - Biaxial and shear test

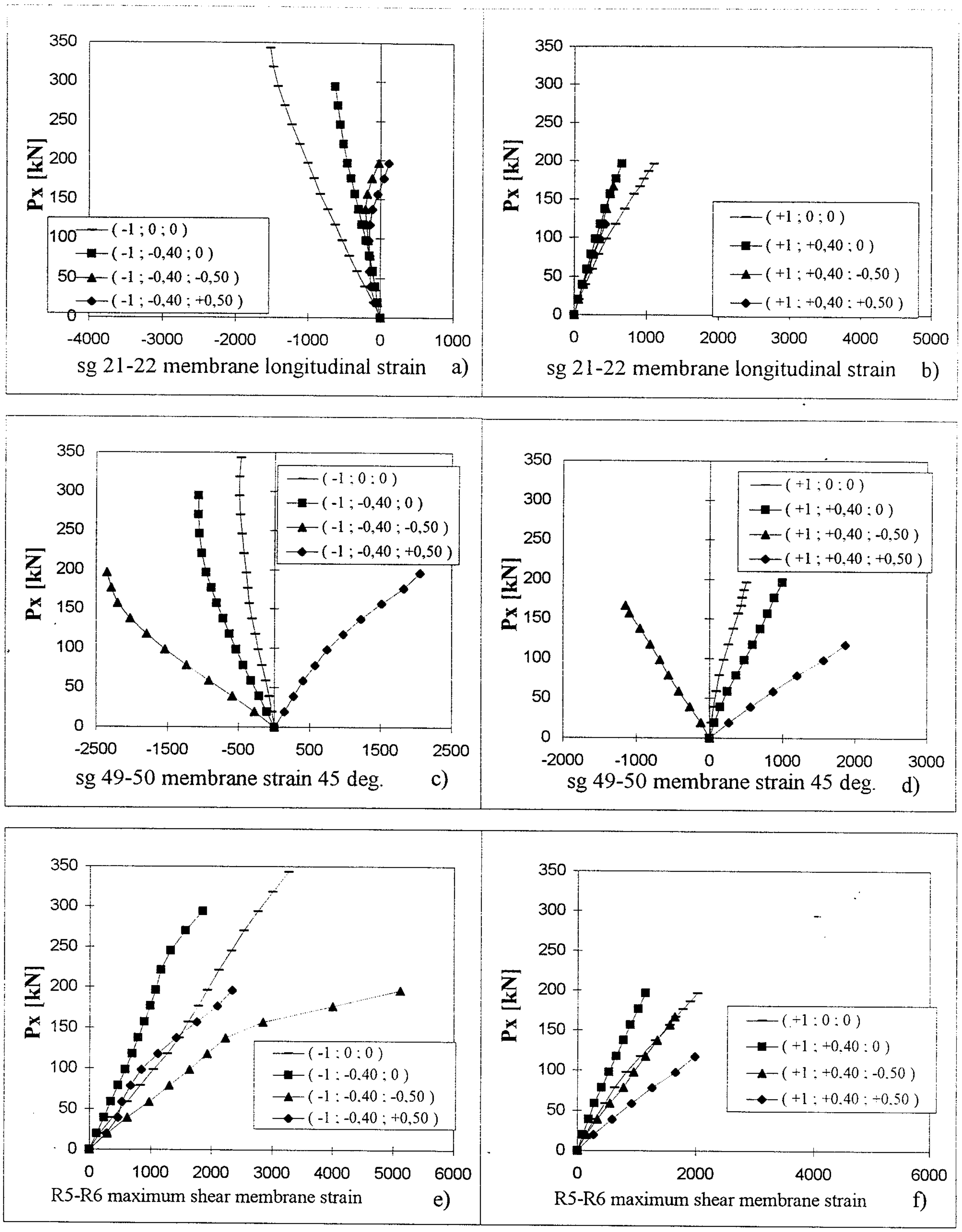

Fig.5 - Comparison between different combined load

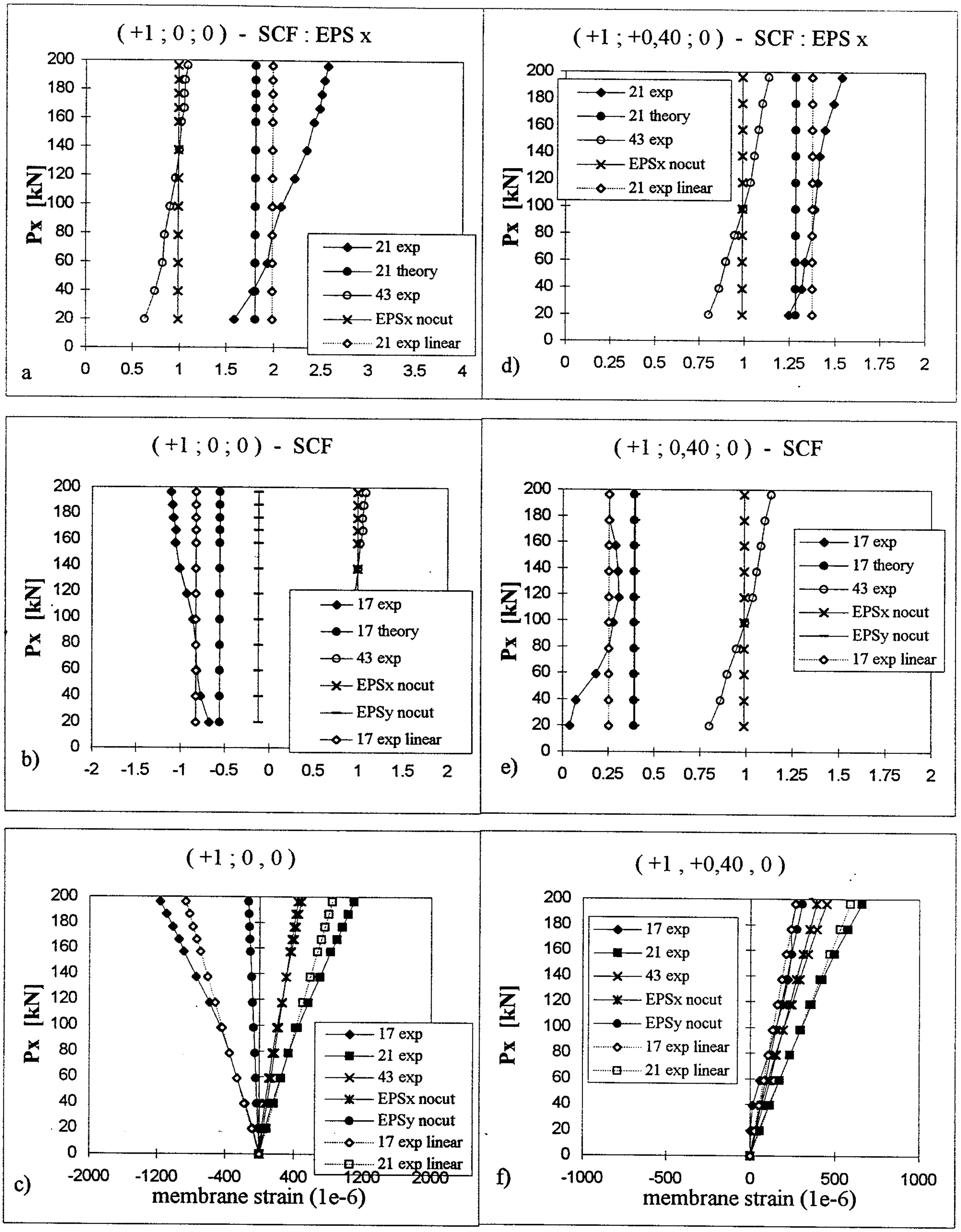

Fig.6 Stress concentration factor (SCF) for uniaxial and biaxial tension load

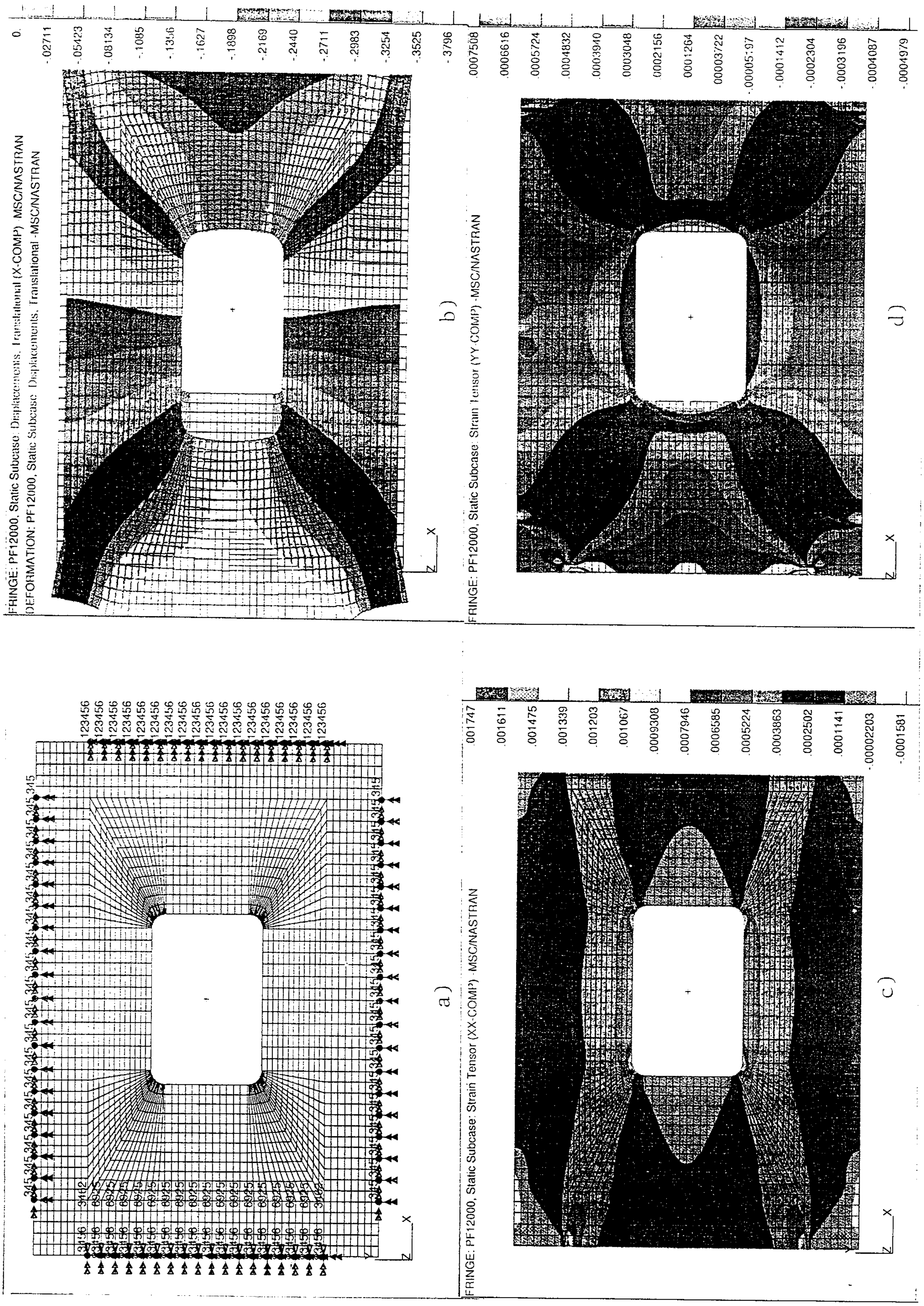
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Fig. 7