Some Analytical and Experimental Methods Definition the Mechanical Characteristics of Sound Absorption Structures

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Abstract--This work describes the analytical technique developed for determining mechanical characteristics of SAS. The procedure of experimental determining the SAS characteristics both in the layer plane and along the honeycomb height has been developed. The results of analytical estimations of mechanical characteristics agree with the experimental data. The analytical estimations are used in the investigations of deformation and load-carrying capability of a cylindrically curved SAS panel. The technique of loading a cylindrical panel with pressure has been developed. The tests have been carried out, and the test results were used for evaluation of calculated estimates accuracy.

1. INTRODUCTION

SAS are widely used in aviation engines. Noise reduction is the main purpose of SAS and, as a rule, they are not mechanical load-bearing structures. At the same time, SAS (even those made from relatively light composites) have rather heavy weight, especially in modern turbofans. This feature of SAS, in combination with their supporting elements' weight, has an adverse effect on engine performance. SAS are ballast in engines. Thus, the problem of using SAS as load-carrying elements of a structure is still urgent despite the permanent improvement in design, manufacturing technique, efficiency, ways of their application (first of all, methods of joining them to load-carrying parts).

The existing techniques for providing the structure reliability are based on the test pyramid [1], they take much time and are expensive. Understanding of SAS behavior under mechanical and acoustic loading permits to decrease the number of tests and to reduce expenses needed for them while maintaining the required reliability levels.

The design techniques of SAS used in aviation engines are similar, in whole, to the techniques of designing honeycomb parts, sandwich structures that are widely applicable (see, for example [2]-[7]). In spite of a relatively high height, SAS are considered as a panel or a shell in designing with corrected characteristics of stiffness. The features of SAS members (perforated skins), their different types (three- or five-layer SAS, different honeycomb height and honeycomb structures) are told on effective mechanical characteristics of SAS. Stiffness in a skin plane, bending stiffness, strength of joints between separate members and other characteristics are used in designing. This requires the development of the adequate techniques for assessing SAS mechanical characteristics. For life estimation it is necessary to know the stress distribution in each member of SAS. That requires a transition from a shell structure to a three-dimensional structure. Three-dimensional models use the characteristics of each separate member of SAS.

The analytical approach to the determination of SAS mechanical characteristics has been developed. The skins and honeycombs of SAS can be manufactured of both metals and composite materials. The technique of averaging is used for the definition of elastic characteristics of perforated skins, honeycomb cores, and SAS. Moreover, the Maxwell and Voigt models are used in calculation of corrected elastic characteristics of multilayer SAS. The experimental technique for defining the elastic and strength characteristics of SAS both in a layer plane and in the direction of the honeycomb height is developed. The results of analytical estimations of SAS mechanical characteristics agree with the experimental data. The technique of SAS cylindrical panel loading with internal pressure has been developed; the tests have been carried out, and the test results are used in estimation of the calculations' accuracy.

2. ANALYTICAL DEFINITION OF ELASTIC CHARACTERISTICS OF SAS AND THEIR MEMBERS

The complex of elastic and strength characteristics of SAS is used during the process of designing structures. The analytical estimation of elastic characteristics is sufficiently reliable while the attainment of the required accuracy for strength predictions presents some difficulties. The analytical technique of defining SAS elasticity characteristics is described below.

SAS represent a mixed structure consisting of several skins and honeycomb layers between them. The load-bearing skin is solid, the other ones are perforated. The mechanical characteristics of skins without perforation as well as those of honeycomb material are considered as specified ones.

2.1. *Elastic characteristics of perforated skin*

The mechanical characteristics of perforated skin depend on behavior of initial material as well as on the arrangement and degree of perforation. They are determined by numerical solution of a problem of real skin tension at a specified value of displacement u_{sp} of a sample free end (rigid loading) by using solid elements of ANSYS.

Fig. 1 shows the typical perforated skin. The distribution of displacements and stresses in skins having 10% of perforation are given in Fig. 2. The pattern of displacements and stresses distribution on the skins with other degree of perforation does not qualitatively differ from the data in Fig. 2.

The distribution of axial displacements u_x along the skin length is uniform, the longitudinal strains ε_x are constant. The stress distribution in the cross-section is intricate. The ratio of average value of longitudinal stresses σ_{xv} to longitudinal strain ε_x was taken as a "corrected" value of modulus of elasticity E_x^{rel} of perforated skin.

$$E_x^{rel} = \sigma_{x.mean} / \varepsilon_x, \ \ \nu_{xv} = - \varepsilon_v / \varepsilon_x. \qquad (1)$$

Here, parameter νxy is Poisson's coefficient. The modulus of elasticity at soft loading with force P is determined from relation

$$E_x^{rel} = P / (F_{rel} \cdot \varepsilon_x), \ \sigma_x = P / F_{rel} \qquad (2)$$

Value of E_{rel} is an area of "effective" cross-section of the perforated skin.

Effective modulus of elasticity is calculated from equality

$$E_x^{eff} = (F_{rel} / F) \, E_x^{rel} \qquad (3)$$

Here, F is a cross-section total area (including voids).

Fig. 3 shows the curve that demonstrates the relation between the imperforated skin's modulus of elasticity E_x^{rel} and the skin material modulus of elasticity depending on the perforation degree and the averaged line of this curve.

If the material of the perforated skins is anisotropic or the pattern of perforation arrangement or perforation form is the reason of the dependence of mechanical characteristics on loading directions then the described above actions should be carried out in the main axes of anisotropy.

2.2. Elastic characteristics of honeycomb cores

The honeycomb cores have an increased stiffness along honeycomb height. The honeycomb stiffness in the skin plane is minor, and the influence of honeycomb sandwich is neglected.

However, the honeycombs may contribute to elastic characteristics in SAS plane under conditions of low stiffness of perforated skins and constrained strains. The problem of tensile-stressed plate composed of honeycomb with different height at rigid loading was resolved for definition of elastic characteristics. Two problems were resolved because the honeycombs have different structures in longitudinal and transversal directions. The displacement and stress distributions in the honeycomb plate with different heights are given in Fig. 4. The technique of elastic characteristic calculation coincides with the above-described technique for perforated skins. Relation between the longitudinal stress σ_x and the longitudinal strain ε_x is considered as a relative elasticity modulus (E_x^{rel}) at i-nodal point. The mean value of modulus $(E_x^{rel})_i$ at all nodal points of cross-section is taken as a relative elasticity modulus. The ratio of transversal strain ε_y to longitudinal strain ε_x with the inverse sign is taken as Poisson's coefficient. A transversal strain ε_y is taken as a ratio of sample contraction to its width. The maximum degree of perforation of the mentioned hereinafter perforated skins does not exceed 10%. In this case, the calculation shows that the influence of honeycomb stiffness in the skin plane is negligible (less than 3%).

2.3. *Elastic characteristics of SAS*

Two techniques are used for the analytical estimation of the effective elastic characteristics of SAS. The effective elastic characteristics of SAS in the direction of a load-bearing layer base were found by mixture formula (Maxwell relation) including well-known behaviors of each layer

$$E_x^{eff} = v_k (E_x^{eff})^k, \ \ \nu_{xy}^{eff} = v_k (\nu_{xy}^{eff})^k, \qquad (4)$$

The transversal characteristics and shear modulus were determined by Voigt relations

$$E_y^{eff} = [v_k / (E_y^{eff})^k]^{-1}, \quad \nu_{yx}^{eff} = v_k (\nu_{yx}^{eff})^k, \quad G_{xy}^{eff} = [v_k / (G_{xy}^{eff})^k]^{-1} \qquad (5)$$

Here, k is the number of SAS member, vk = hk/h – relative thickness of k-elements, h ($h = \sum h_k$) - total thickness of SAS cross-section.

The solution of a compound structure tensile-stressed plate problem at a given displacement of the free end is the second technique of effective elastic characteristics estimation. In this case, the mechanical characteristics of all SAS members are considered well-known – they can be determined by either above- described analytic technique or experimentally. The definition technique of the SAS relative and effective characteristics coincide with the above-described

technique for perforated skins. The calculated relations between SAS relative elastic characteristics and elasticity modulus of the load-bearing layer are given in table 1. Fig. 5 presents the distribution of SAS stresses defined by ANSYS.

Table 1 Relative values of SAS relative elasticity modulus defined by two approaches

Approach	Estimated characteristics	
	Elasticity modulus, GPa	Poisson's coefficients	
	$E^{exp}{}_x/E_x$	ν_{xy}	ν_{xz}
Finite element	0.97	0.31	0.31
Relations (4)-(5)	0.98	0.3	0.3
Experimental	1.0	0.3	0.3

The SAS elasticity moduli defined using FE ANSYS and relations (4)-(5) have identical values.

SAS is considered as a perfect structure when determining effective elastic characteristics by developed analytical technique. In practice, all SAS contain technological imperfections [8] in the form of fiber ruptures, matrix or (and) interface damages, hole surface defects, face wrinkling and crimpling, burrs in the area of honeycomb and skins joints, and other. All this is not taken into consideration for the described analytical approaches. The results of analytical predictions must be confirmed by tests or, on the other side, they can serve as a criterion of perfection of SAS manufacturing technique.

3. EXPERIMENTAL DETERMINATION OF SAS CHARACTERISTICS

The complex of SAS elastic and strength properties is determined experimentally. SAS represent compound structures, and SAS failure may take place either in their separate members or in the areas of their joints. In this case, the SAS stiffness and strength characteristics are determined in the tests of samples of different forms. Below, there is a description of SAS samples' structures that were used.

3.1.Experimentally determined characteristics

Fig. 6 shows the sample form (shape) used for definition of elasticity characteristics and strength at static tension as well as stress rupture and low-cycle fatigue.

The elasticity and strength characteristics at static tension and compression as well as stress rupture and low-cycle fatigue at either tension or oscillating loading in the direction of honeycomb height are determined by tests [9] of samples (Fig.7).

The elasticity and strength characteristics at static shear of honeycomb sandwich relative to skins are found from the tests [10] of samples (Fig.8).

High-cycle fatigue is determined by tests of samples (see Fig.9) at the normal mode of vibrations (mainly, by first bending mode). Such samples are also used for damping definition.

3.2. Test results

Below some test results of SAS are presented.

3.2.1. SAS characteristics in skin plane

Typical stress-strain curves are given in Fig. 10. Elasticity modulus and Poisson's coefficient are determined at 50% of limiting strain.

The failure of practically all samples took place in the linear strain area, as a rule, with exhaustion of carrying capability of the skin having the largest degree of perforation (see Fig. 11). This circumstance demonstrates the uniformity of strains in separate members of SAS.

The tests showed that both the effective modulus and the strength of SAS samples having low height more than 2 times exceed such parameters of samples with high height. It is possible that the SAS height influences their mechanical characteristics. Finally, it should be noted that the analytical and experimental results differ slightly (see table 1).

3.2.2. Honeycomb sandwich characteristics

Fig. 12 shows the honeycomb samples prepared for tests along their height at tension and compression.

Tension.

The procedure of tests is shown in Fig 12. The displacements of active capture are measured using a digital indicator of displacements. The results of samples tension test are presented in table 2. The elasticity modulus and strength limit at tension were determined by tests of different samples. Fig. 13 shows the type of samples failure. The tested samples have failure in the area of honeycomb cores (having low height) joint to the inner perforated skin. It is necessary to notice that the spread of elasticity modulus values is not statistically essential whereas the spread of ultimate strength values is more essential.

Compression

The results of samples compression test are presented in table 2. Again it can be seen that the dispersion of elasticity modulus values is not considerable. However, their values are less than the values of elasticity modulus at tension by a factor of 1.5. Apparently, this experimental result can be explained in the following way. The middle perforated layer influences the total resistance of a sample at tension, and at compression the honeycomb sandwich only contributes to load-carrying capacity. The influence of honeycomb height on strength value is not determined. At the same time, the samples with a higher height had lower strength at compression. Loss of stability is a typical failure of honeycomb samples with a high height.

The adhesion between honeycombs and skins does not have such influence on the ultimate strength at compression as it has at tension. In connection with this, the strength at compression exceeds the one at tension by a factor of eight.

Table 2 Results of samples test for tension and compression

	Strength		Elasticity modulus		Limited strain
	σ^{eff}	σ^{rel}	E^{eff}	$E^{rel,}$	strain
Tension	0,091	2,048	0.509*		-
	0,080	1,802	0.515*		-
	0,092	2,063	0.496*		-
	0,074	1,667	0.579*		-
	0,101	2,27	0.582*		-
Compression	0,148	3,314	0.367	8.23	0,0009
	0,237	5,326	0.380	8.61	0,0008
	0,142	3,188	0.362	8.11	0,00075
	0,211	4,73	0.355	7.97	0,00085
	0,193	4,320	0.343	7.70	0,0008

3.2.3. SAS characteristics at shear

The results of testing the samples of two types are presented in table 3. The tested samples differed in honeycomb height. The typical failure at shear is shown in Fig. 14.

Summarizing, one can notice:

– the tests at shear were more time-consuming,

– the elasticity modulus of samples with low height are higher than those of samples with high height,

– the honeycomb's shear strength values exceeded their strength values at rupture.

Table 3. Results of shear tests of samples having different height

Samples		Strength	Elasticity Modulus	Ultimate strain
High	1	0.31	70	1.12
	2	0.7	61	1.77
	3	0.53	65	0.81
	4	0.64	66	1.29
	5	0.47	65	1.1
		0.56; 0.15;27%	65.4; 2.8; 5%	1.22
Low		0.52; 0.15;29%	83; 11.9; 14%	2.39

4. TESTS OF SAS FULL-SIZE PANELS

Neither calculations nor test results of simple-form samples can guarantee the determination of full-scale parts' mechanical characteristics. In this connection, the technique of testing the SAS full-size panel under inner pressure was developed. The samples were cut out from real SAS in the form of cylindrical panels. The developed earlier device allows to simulate the on-engine fixation conditions and static loading with inner pressure. The device and the general view of the test rig are given in Fig 15. The resistive-strain gages were pasted on load-bearing skins. The strain-stress curves were received in the tests. The experimental results are presented in the form of the generalized (stress-strain) curve and are given in Fig. 15. In this figure there are also presented the experimental values of elasticity modulus and Poisson's coefficients. The fracture pattern is presented in Fig.16.

5. CONCLUSIONS

The technique of elastic characteristics analytical definition for both SAS members and SAS as a whole has been developed.

The tests aimed at definition of elasticity and strength characteristics at longitudinal tension in the skin plane at both tension and compression along the honeycomb core height and, finally, at shear in the skin plane have been carried out.

The procedure of SAS panels testing for strength has been developed.

The results of the work show the following:

– calculated values of elastic characteristics agree with experimental data,

– spread of elastic characteristics' values is less than those of strength ones,

– elasticity moduli at tension and compression along honeycomb height are different,

– loss of honeycomb stability is a typical failure mode at compression along honeycomb height,

– SAS panels of lower height are stiffer at shear.

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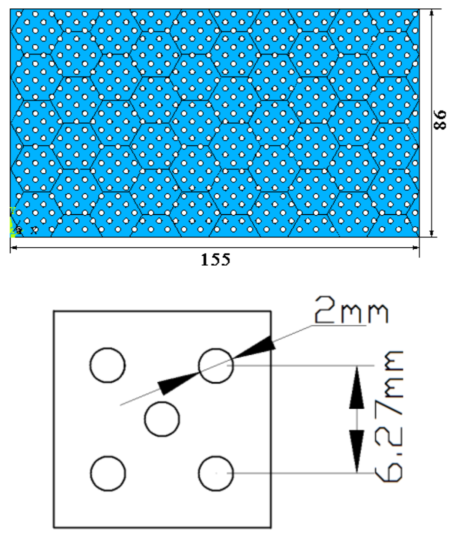

Fig.1. The form, distribution and sizes of a typical perforated skin.

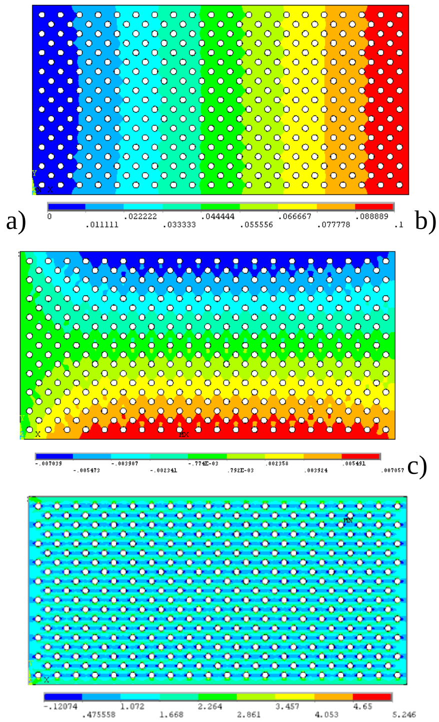

Fig.2. Longitudinal displacements (a), transversal displacements (b) and longitudinal stresses (c) of perforated skin at tension (perforation takes 10% of the skin area)

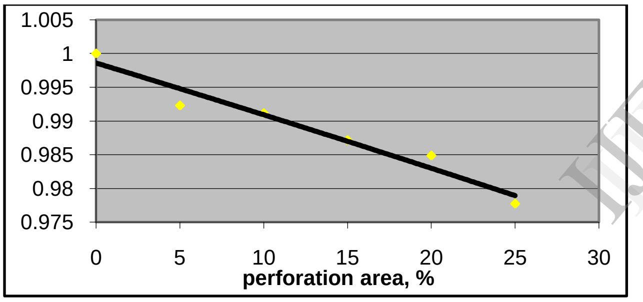

Fig.3 Relations between effective elasticity modulus of perforated skin and load-bearing capacity of imperforated skin versus perforation area (perforation degree)

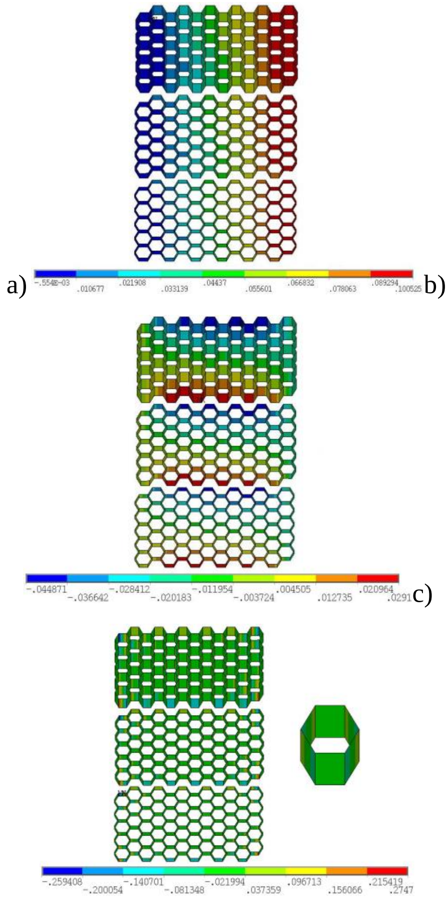

Fig.4. Longitudinal displacements (a), transversal displacements (b) and axial stresses (c) of honeycombs having different height (7, 10, 20 mm) at longitudinal tension

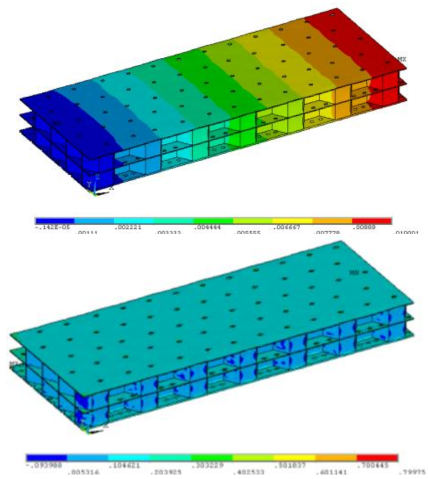

Fig. 5. Longitudinal displacements and axial stresses distribution in SAS at tension

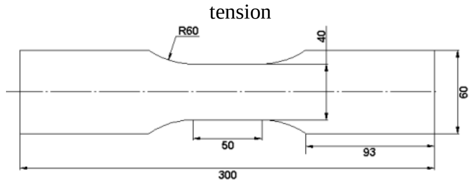

Fig. 6. SAS sample for tension tests in skin plane (sizes are given in mm)

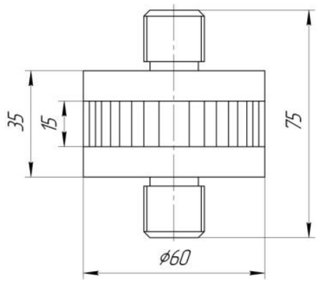

Fig.7. SAS sample for tension-compression tests of honeycomb in the direction of its height (sizes are given in mm)

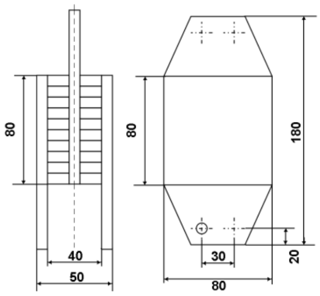

Fig.8. SAS sample for shear tests (sizes are given in mm)

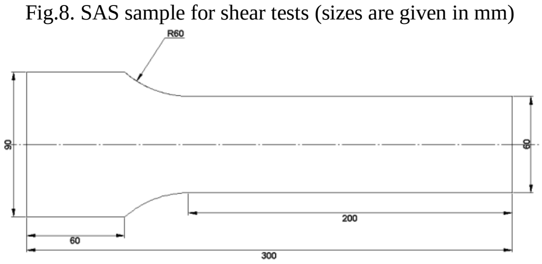

Fig.9. SAS sample for endurance and damping tests (sizes are given in mm)

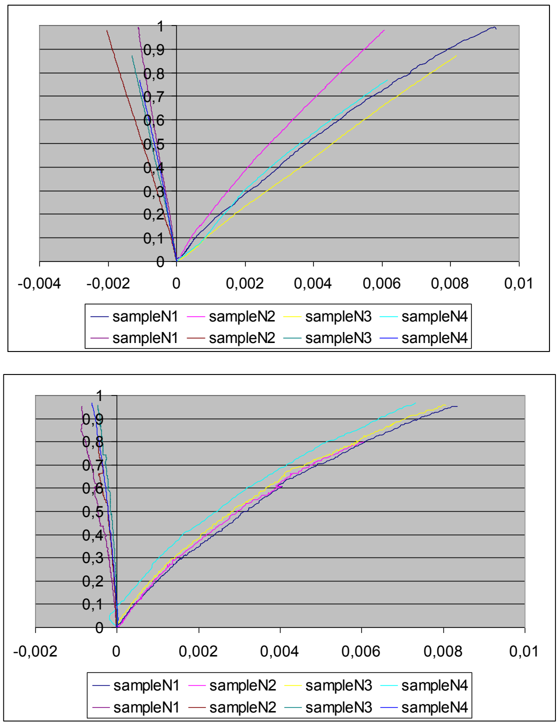

Fig.10. Typical strain-stress curves obtained at tension tests in SAS skin plane

Fig.11. Typical failure at tension in SAS skin plane

Fig.12. SAS samples during tests for compression along honeycomb height

Fig. 13 Samples after testing for tension along honeycomb height

a)

b)

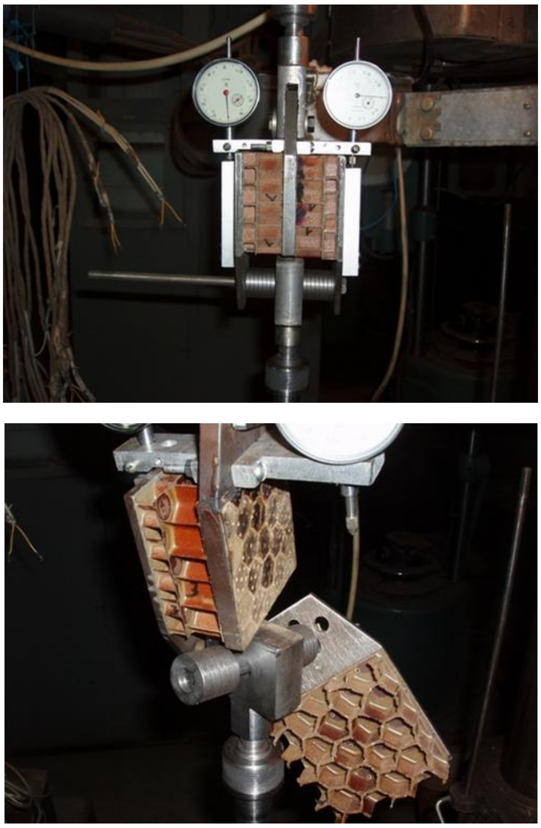

Fig. 14. SAS sample shear testing
(a) before testing and, (b) after testing

a)

b)

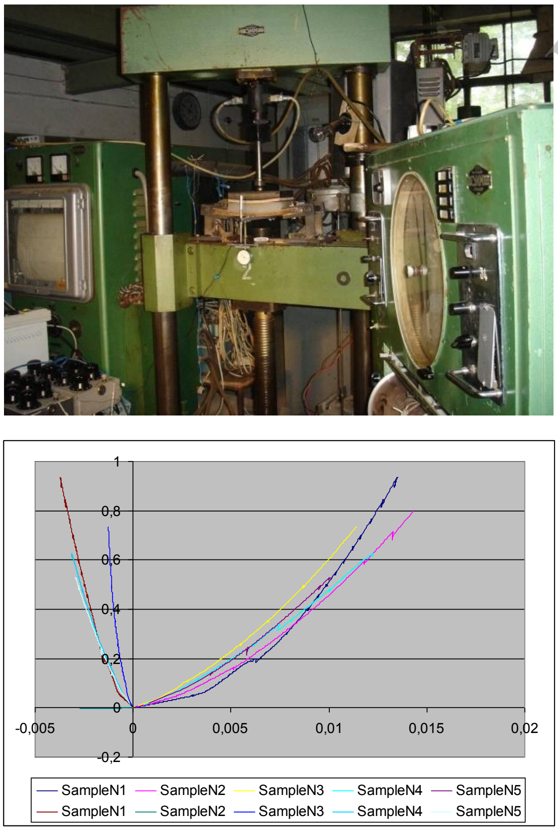

Fig. 15. Full-scale SAS panel on the test rig (a) and generalized stress-strain curves obtained in full-scale SAS panels' tests (b).

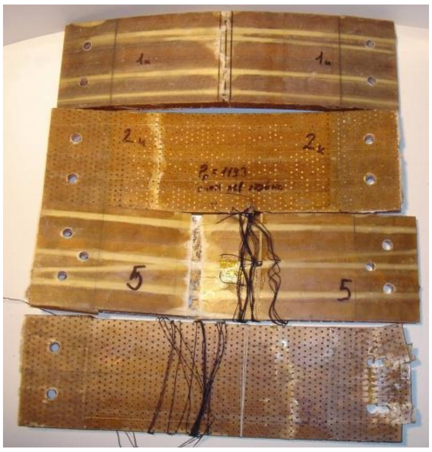

Fig. 16. Kinds of failure of full-scale SAS panels