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ON THE USE OF A SYNTACTIC FOAM AS CORE FOR SANDWICH PANELS AND AS EXTERNAL COATING FOR PRESSURISED PIPELINES

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Abstract. *This work reports the main results of an experimental and numerical investigation on the mechanical properties and possible engineering applications of a syntactic foam. This foam consists of an epoxy resin matrix embedding randomly dispersed hollow glass microspheres made with a borosilicate glass; they present an average diameter of 70 μm and a wall thickness of 0.58 μm. To characterise this material, an extensive experimental programme has been carried out. The purpose of this paper is twofold: first, part of the experimental results obtained are briefly presented; second, two possible uses of the syntactic foam are discussed. In the first case the foam is used as the core of a composite sandwich conceived as a lightweight material for naval engineering applications; in the second case, the syntactic foam is employed as external coating of steel pipelines which are laid on the sea bed for pressurised oil transmission. This second application is explored due to the fact that the syntactic foam displays good mechanical properties and is at the same time a good thermal insulator.*

1 INTRODUCTION

This note presents some of the salient results of a study on the possible applications of a syntactic foam[1,2] consisting of hollow glass microspheres embedded in an epoxy resin matrix. The mechanical characterisation of the material has been achieved through an experimental campaign and the development of practical engineering-oriented constitutive models. Their potentialities have been checked trough FE simulations. A complete description of the experimental results and numerical simulations can be found in references[3-5].

The first application considered here for the syntactic foam under study is related to the design of a composite sandwich[6,7] used as a lightweight material in naval engineering. The sandwich core is made with the syntactic foam, whereas the sandwich skins are glass fibre/polymer matrix composites. To reduce possible delamination damages, the interior layers of the skins are connected to each other by piles which cross the syntactic foam core. The validity of this proposal has been investigated through an experimental characterisation of sandwich panels and numerical FE simulation of three- and four- point bending tests[4].

In the second application discussed here, the syntactic foam is conceived for the external coating of steel pipelines laid on the sea bed for pressurised oil transmission[8]. Indeed, high thermal insulation performances are normally requested to these underwater pipelines in order to limit the deposition of heavy oil fractions that may partially or even totally plug the pipeline. In this respect a possible design concept consists of an highly efficient thermal insulating material surrounding a pre-insulated inner steel pipe; a water proof steel shell should be also added externally to shield the low resistance insulating material. In this work, a preliminary study is presented in order to verify if the syntactic foam is able to sustain the stresses induced by both internal and external pressures, even without the presence of the additional external steel shell.

2 SYNTACTIC FOAM

The syntactic foam under study was manufactured by a former branch of Intermarine S.p.A. (Italy) under the trademark Tencara 2000™. The foam is assembled with an epoxy resin matrix which embeds hollow air-filled glass microspheres. The matrix is made with SP Ampreg 20™ epoxy resin treated with SP Ampreg™ UltraSlow hardener allowing extended working times. Air-filled hollow glass microspheres named 3M Scotchlite™ Glass Bubbles, type K1, are manufactured with a water resistant, chemically stable, borosilicate glass. Bubbles have an average diameter of 70 μm and an average wall thickness of 0.58 μm. The syntactic foam is prepared by mixing resin and hardener under vacuum and by adding microspheres repeatedly until full homogenisation is attained. The density of the resulting syntactic foam[3,5,9] averages 0.55 g/cm^3.

2.1 Experimental results on the syntactic foam

Some of the results of the uniaxial tension/compression and Notched Three Point Bending (NTPB) tests performed on the Tencara 2000™ syntactic foam specimens are reported in this Section. The complete set of experimental results is available in references[3,5]. Specimen dimensions have been chosen according to UNI and ASTM standards for concrete and composite materials in a way consistent with the characteristics of the loading devices. The shapes and sizes for compression (tension) tests were determined according to ASTM D 695 M-91 (ASTM D 638) standard for composites. More precisely, the specimens for the compression tests were circular cylinders with 30 mm diameter and 75 mm height, whereas axisymmetric bars with tapered cross-section 10 mm in diameter were used for the tension tests. In Fig. 1 the stress/strain curves of the uniaxial tests are reported, while in Table 1 the main mechanical parameters obtained from the uniaxial tests are collected.

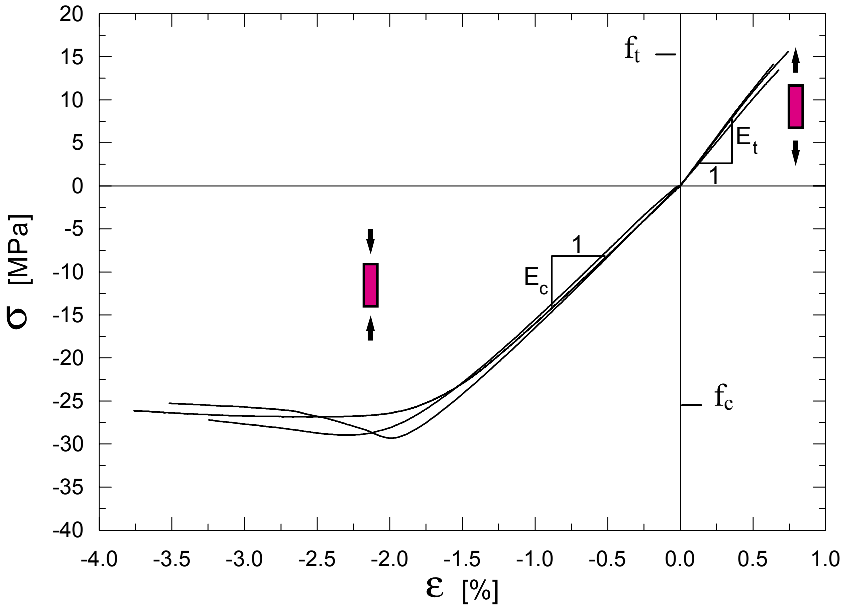


Figure 1. Uniaxial tension/compression nominal stress/strain curves of the syntactic foam (traction positive).

E_c [MPa]	E_t [MPa]	G [MPa]	ν	f_c [MPa]	f_t [MPa]	α [1/°C]
1600	2200	780	0.34	28.4	15.6	$7.5\ 10^{-5}$

Table 1. Mechanical characteristics of the syntactic foam.

The tensile strength, f_t=15.6 MPa, is about 55% of the compressive strength, f_c=28.4 MPa, whereas the Young's modulus in tension, E_t=2200 MPa, is about 35% greather than the Young's modulus in compression, E_c=1600 MPa. This phenomenological feature is not pointed out in the available literature on syntactic foams. The fact that the specimens tested in tension belonged to a second set of syntactic foam specimens which displayed lower degree of porosity and compressive stiffness about 15% higher allows to explain only partially this characteristic. The remaining difference (about 20%) should be mainly attributed to the presence of air bubbles between matrix and filler. In fact, further experimental tests on syntactic foams prepared with more careful manufacturing techniques did not show appreciable differences in elastic stiffnesses[5]. Accordingly, the measured tensile modulus would be the intrinsic elastic stiffness of a syntactic foam without unintentionally included voids. This hypothesis is corroborated by the experimental values obtained for the Poisson's ratio ν=0.34, measured both in compression and tension tests, and for the shear modulus G=780 MPa, measured by means of torsion tests on specimens of the same type as those of the tensile tests. Indeed, this value of G is quite in agreement with a shear modulus evaluated with the classical formula for isotropic linear elastic materials, where the tensile modulus is taken as Young's modulus.

The compression behaviour is rather ductile; the collapse mechanism is preceded by strain localisation along a shear band inclined to an angle of about 45° with respect to the loading axis. On the contrary, the response under tension is perfectly brittle with rupture on a section perpendicular to the loading axis.

The dimensions of the notched specimens for the NTPB tests have been chosen according to the ASTM E 399 standard as a compromise between optimum size for the testing machine and small-enough size to avoid too brittle response: height =14 mm, length =60 mm, width =7 mm, notch length =7 mm, span length =50 mm. Tests were made under vertical displacement control, since the small specimen dimensions of the specimens did not permit to drive the test under crack-mouth opening control. The behaviour is quasi-brittle: a practically-vertical load drop follows the peak, after which a softening tail develops. The failure of all specimens occurred at mid-span section, with a crack departing and propagating vertically from right above the sharp-edged notch. The experimental load/displacement curves are shown in Fig. 3, together with the results from the numerical simulations presented in Section 2.2.

2.2 Numerical FE simulations of the syntactic foam

Starting from the experimental results, two different models have been considered to reproduce the mechanical properties of the syntactic foam: a modified Drucker-Prager elastoplastic model (smeared approach) and a cohesive crack model (discrete crack approach). Both were calibrated on the basis of the experimental tests and were separately used and compared in the numerical FE simulations[3]. Considering the NTPB tests, the FE simulations obtained with the second model gave results particularly in good agreement with the experimental data.

The cohesive crack normal stress/opening displacement law adopted is trapezoidal (Fig. 2). At varying parameter β ($0\leq\beta\leq1$), it is possible to include both the classical linear case often reported in the concrete literature[10,11] (β=0) and the rectangular Dugdale-type cohesive law[12] (β=1), already used in the past for modelling polymer fracture[13].

Figure 3 illustrates the simulations of the NTPB test in terms of the load/vertical displacement curves for different values of the parameter β. It is possible to note that the softening tail is captured well, whereas the peak load is underestimated with the linear cohesive crack model (β=0); the Dugdale-type law (β=1) renders instead the best peak prediction and brittler, almost vertical, initial post-peak branch with full quantitative agreement with the experimental results. In these simulations, the bulk material has been considered linear elastic and bimodular, whereas all nonlinearities have been confined to the cohesive crack law implemented by horizontal nonlinear springs on the FE nodes of the ligament section at mid span[3].

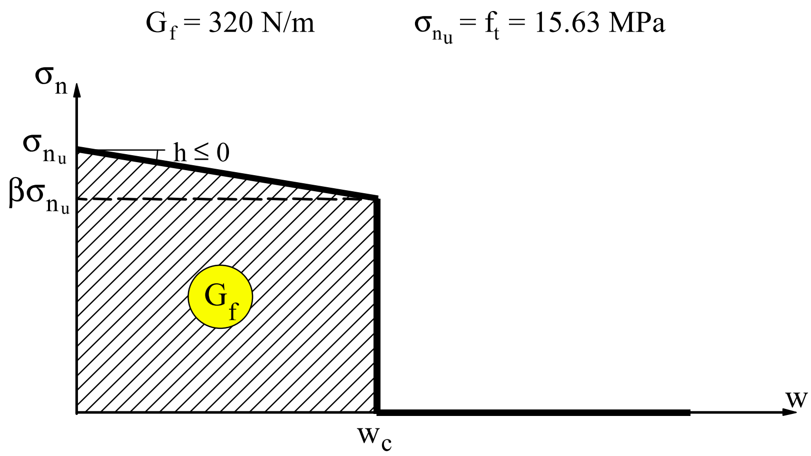


Figure 2. Trapezoidal cohesive crack model adopted in the numerical FE simulations.

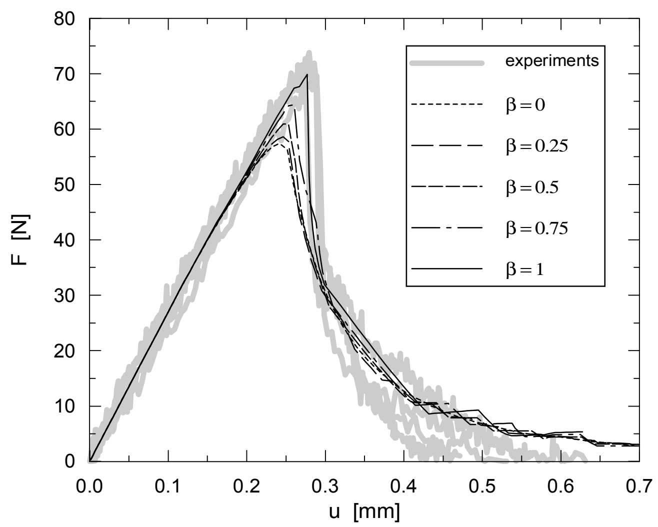


Figure 3. Load/displacement curves with the discrete crack approach: comparison of experiments and numerical results for different values of β.

In conclusion, it seems that the hypothesis of a material that is able to sustain a constant tensile stress until a critical opening displacement is reached, and then fails abruptly, seems the nearest to phenomenological reality for the foam under study.

3 SYNTACTIC FOAM AS CORE OF COMPOSITE SANDWICH

As described in the Introduction, in the first engineering application considered here the syntactic foam under study is used to manufacture a composite sandwich. The *core* of this sandwich (Fig. 4) is built starting from a textile composite[4,14], pre-impregnated first and then filled with the syntactic foam. To improve the mechanical resistance in bending, two extra *skins* of ROVIMAT 1200™ (made of glass-fibres and polymer matrix and with a thickness of 2.5 mm) are added on the external facings of the sandwich. The global sandwich thickness is t=16 mm.

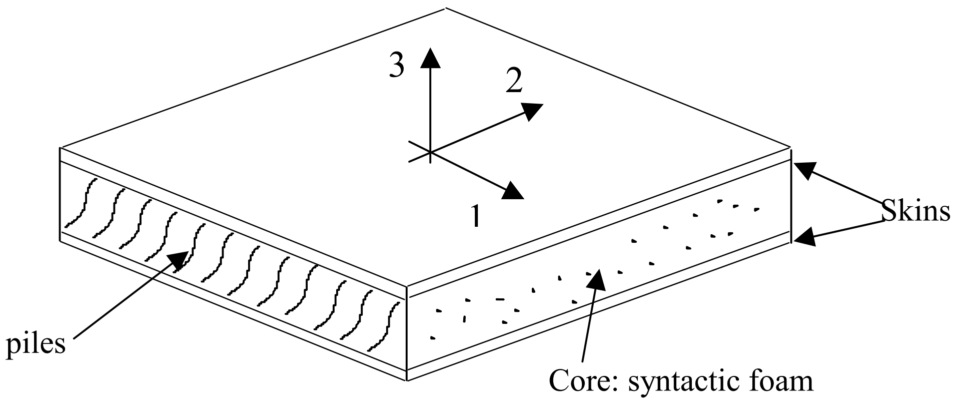


Figure 4. Sandwich composite.

3.1 Experimental results on the composite sandwich

Following the ASTM C393-94 standard for sandwich structures, rectangular plates with the dimensions (height=16 mm)x(length=110 mm)x(width=30 mm) were prepared to be tested in Three and Four Point Bending configurations (TPB, FPB) over a span of 60 mm. Figure 5 shows typical load/displacement curves concerning the FPB tests.

The differences in the curves of Figure 5 are due to the various mechanisms that lead to the final collapse of the specimens. The main recorded mechanisms were: a) unsymmetric collapse with the formation of a single 45° inclined crack in the core; b) symmetric collapse with development of two 45° inclined cracks in the core; c) extra skin collapse in tension; d) extra skin delamination.

3.3 Numerical FE simulations of the composite sandwich

To simulate the sandwich bending tests, the following simplifying assumptions were introduced: a) the skins were taken as homogeneous and orthotropic; b) the core was assumed as homogeneous and isotropic; c) the piles were not considered in the numerical model; d) the behaviour of both the skins and the core was assumed to be elastic-brittle. For the elastic stiffnesses and the critical stress of the skins the values obtained from separate tensile and compressive tests on the skins alone were used[4,5].

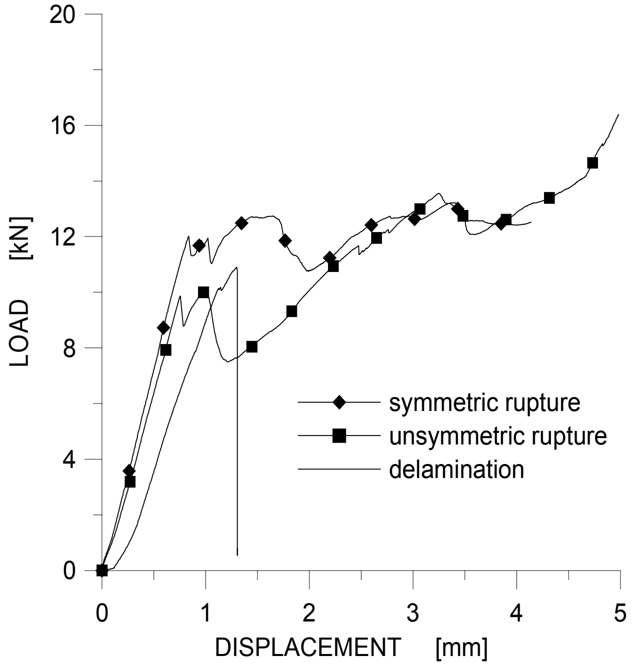


Figure 5. Load/displacement curves for TPB tests.

The Poisson's ratio and the average critical stress threshold in tension for the core were those of the syntactic foam. On the contrary, as obtained by flat-wise compression tests on sandwich specimens, the presence of the piles reduces the elastic stiffness of the core with respect to the stiffness of the plain syntactic foam. The values adopted are the following:

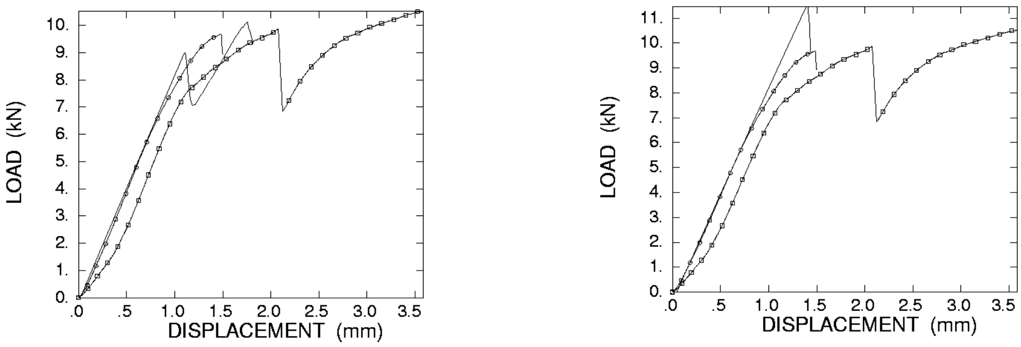
skins: $E_1 = 13153 \;\; \text{MPa}$; $E_2 = 14707 \;\; \text{MPa}$; $\nu = 0.2$; $\sigma^{cr} = 225 \; \text{MPa}$ (1)

core: $E_{core} = 1100 \; \text{MPa}$; $\nu = 0.34$; $\sigma^{cr} = 14.5 \; \text{MPa}$

where indeces 1and 2 refer to the in-plane axes of the reference frame in Fig. 4.

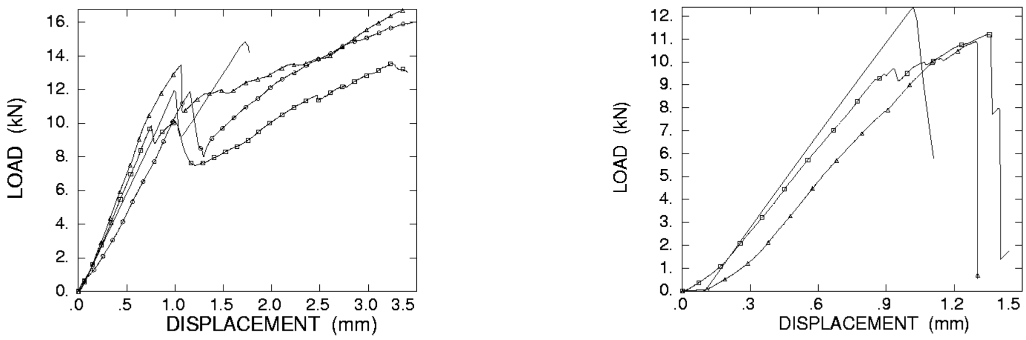
The simulation of the progressive damage in the specimen has been obtained by a simple computational technique of local stiffness release: when a threshold value of a scalar failure index is reached in the single Gauss Point, the tensile elastic modulus E_t is annihilated locally. Accordingly, the contribution of that Gauss Point to the element stiffness matrix is then brought to zero. For this simple procedure, implemented through a user subroutine, different failure indexes may be considered, either based on local strain or stress states. In the numerical results presented here, as probably the most natural choice in brittle fracture, the local stiffness release criterion is based on the value of the maximum principal stress σ_1.

To simulate the different kinds of sandwich collapse (core or skin collapse, delamination) the numerical analyses were done by activating separately the failure criterion in the core, in the skins or in the line of elements near the interface between extra skin and core. Figures 6 and 7 present comparisons between the experimental and numerical results for TPB and FPB specimens, respectively. It is possible to notice that the devised simplified procedure captures the global failure load of the sandwich quite correctly.



(a) (b)

Figure 6. Experimental (marked lines) vs. numerical (continuous line) load/displacement curves of the TPB tests: (a) core rupture; (b) skin rupture.



(a) (b)

Figure 7. Experimental (marked lines) vs. numerical (continuous line) load/displacement curves of the FPB tests: (a) core rupture; (b) delamination.

4 SYNTACTIC FOAM AS EXTERNAL COATING

In this Section, the mechanical behaviour of the syntactic foam to be used as an external coating for pressurised under-water steel pipelines is critically explored. The considered configuration consists of a pre-insulating inner steel pipe surrounded by a pipe of syntactic foam, without the presence of a further outer steel shell (Fig. 8).

The purpose of the study is to investigate if the syntactic foam is able to sustain the stresses due to the internal and external pressures. This preliminary study concerns only the elastic analysis of a pipe made by two different materials under simple axisymmetric loading conditions. Obviously, conclusive remarks on the possible use of this syntactic foam could be drawn only by analysing the pipe during real installation and operating conditions.

The geometrical and material data considered for the inner steel pipe are as follows: the outer diameter is 220 mm; the thickness is 20.5 mm; the Young's modulus and Poisson's ratio are 206000 MPa and 0.3, respectively, whereas the thermal expansion coefficient is 1.2 10^{-5} 1/°C. The experimental results described in Section 2 have been used to characterise the syntactic foam coating. Its thermal expansion coefficient is equal to 7.5 10^{-5} 1/°C. Three different thicknesses (4.45 cm; 8.90 cm and 13.3 cm*)* have been considered in order to study the influence of this parameter on the numerical results. The environmental and loading conditions applied to this system are the following: internal fluid pressure and temperature equal to 15 MPa and 60 °C, respectively, whereas the water depth is in the range 1000/2500 m with a temperature of 4 °C. The variation of the temperature along the pipe thickness is assumed to be logarithmic.

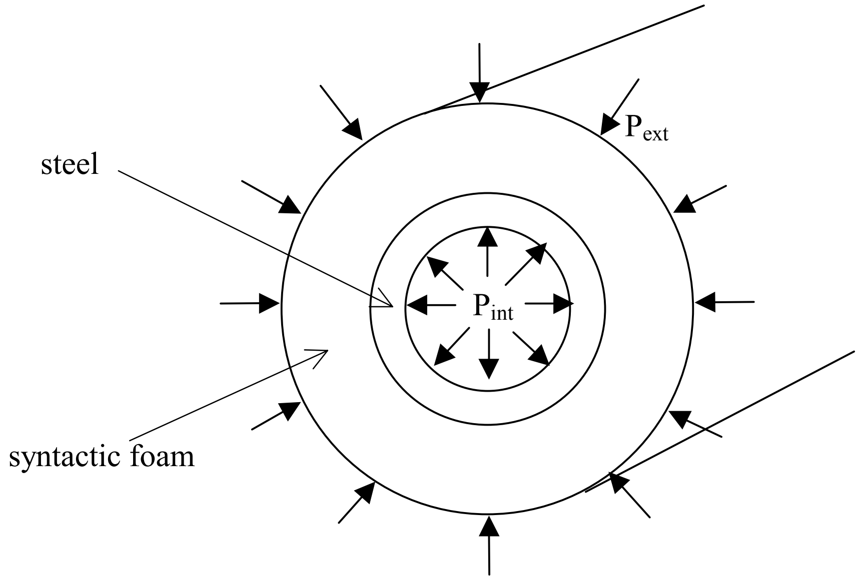


Figure 8. Schematic representation of pressurised under-water steel pipeline with syntactic foam coating.

Figures 9 and 10 show the radial (Fig. 9) and circumferential (Fig. 10) stresses as a function of the pipe ray, for the intermediate coating thickness and for four different values of the external pressure.

It is possible to note that the radial stress in the syntactic foam exceeds the ultimate compressive strength f_c=28.4 MPa (see Table 1) only when the external pressure amounts to 25 MPa. On the contrary, the circumferential stress (and also the axial stress) in the syntactic foam is always lower than the critical stress. The obtained stress distributions strongly depend on the different values of stiffness and thermal expansion coefficient of steel and syntactic foam. The maximum value of radial stress in the syntactic foam should, more realistically, be compared with a critical value obtained experimentally in triaxial loading conditions. This last value has been shown[1] to be significantly greater than the uniaxial compression limit.

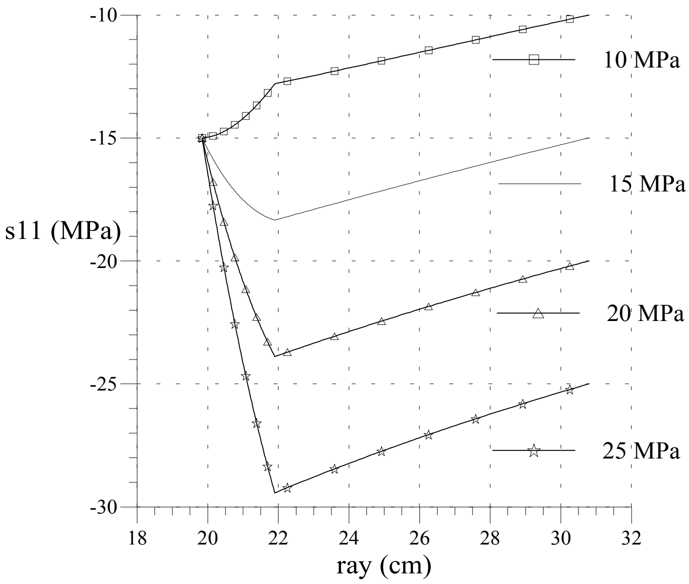


Figure 9. Variation of radial stress as a function of ray for four different values of external pressure (coating thickness is 8.90 cm).

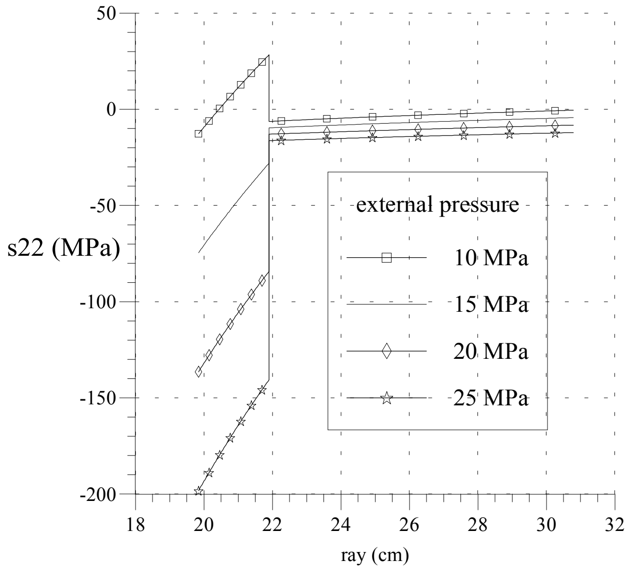


Figure 10. Variation of circumferential stress as a function of ray for four different values of external pressure (coating thickness is 8.90 cm).

Figure 11 shows the variation of the radial stress computed for two values of the external pressure (10 MPa and 25 MPa) and for three values of the syntactic foam pipe thickness.

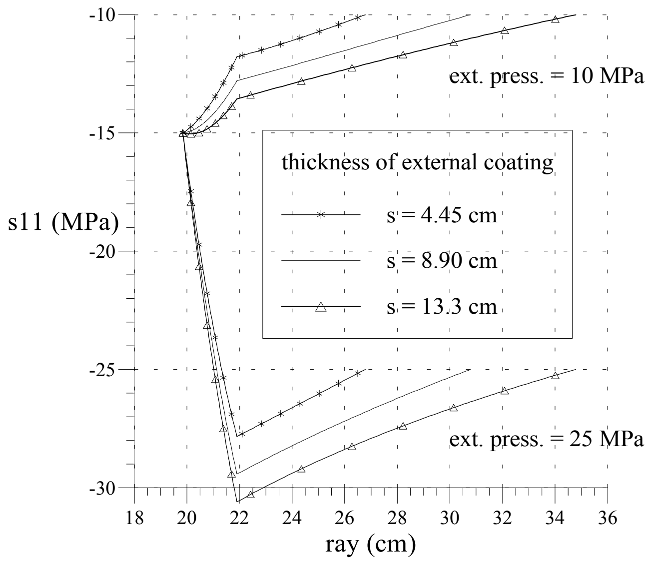


Figure 11. Variation of radial stress as a function of ray for two different values of external pressure and for three thicknesses of the external coating.

It is possible to note that the intensity of the radial stress in the syntactic foam increases whit the thickness. The variations of the circumferential and axial stress components are not significant.

The idea of employing the syntactic foam as external coating of pressurised pipes is based on its high thermal resistivity, low degree of water absorption and good compression resistance. The above preliminary and partial results seem to confirm this hypothesis. Obviously, to obtain more comprehensive and reliable results, a complete study must be undergone. This should imply experimental tests and thermo-mechanical numerical simulations involving not only the pipe section, but also the axial direction along the pipe.

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