An Innovative Thermal and Acoustic Insulation Foam for Naval Fire Doors Characterization and Study With FEM Analysis

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Abstract. An innovative acoustic and thermal insulating foam was developed starting from fiberglass waste. In this work, the thermo-mechanical response of a fire door containing the foam as insulating material is considered and also the acoustic properties are investigated. In order to comply with the certification process provided by 2010 FTP Code, fire doors must undergo a standard fire test where a prototype is subjected to temperature up to 950°C. A realistic simulation of the heating process is useful during the design phase for the evaluation of the fire door behaviour without prototype construction. A RINA report of a standard fire test performed on the same fire door containing rock wool as insulating material is used to validate the model. Foam thermal and mechanical properties needed for the numerical analysis (e.g. thermal conductivity, specific heat capacity, Young's modulus) are obtained through experimental tests. The results pointed out an improved acoustic insulating performance respect to rock wool and comparable thermo-mechanical properties. The foam is a promising alternative to rock wool thanks to the environmental benefits derived from fibreglass recycling and the absence of fibre release.

Keywords. Fire door, acoustic insulation, fire test, finite element modelling, thermo-mechanical analysis, fiberglass recycling.

1. Introduction

The commercial success of a ship depends directly on the quality of the parameters influencing life passenger on board. Among these, noise is perhaps one of the most important [1]; Classification Societies have published rules to establish the comfort class of a ship [2,3] and the shipowners' requests for noise reduction are increasingly stringent. Another fundamental aspect is the safety of passengers and crew; therefore, fire resistance characteristics are required by Classification Societies [4]. For these reasons, materials that combine characteristics of sound insulation with those of thermal insulation are used on board, offering fire protection and high comfort at the same time.

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Thanks to its properties and low cost, nowadays rock wool is the most used insulator [5]. However, this material releases fibers if managed, with risks for operators' health [6]. Therefore, there is a real interest in finding substitutes [7].

In this work an innovative insulating foam is considered as substitute of the rock wool; it is produced from fiberglass waste, a composite material widely employed in the nautical sector, but difficult to reuse [8,9]. Foam's patented production process [10] allows fiberglass recovery through an eco-friendly method where only natural additives are used, no harmful gases are produces, and the use of high temperatures is not necessary. Moreover, the foam does not release fiber.

The aim of this work is to generate a numerical model for the simulation of the fire-resistant test required by the International Code for Application of Fire Test Procedure (FTP Code). The numerical modelling would permit to save time and money during the design phase; it allows to evaluate the performances of the fire door containing the innovative foam, limiting the number of prototypes to be constructed and tested.

The acoustic, mechanical and thermal characteristics of the foam were measured experimentally and compared to rock wool properties. The model geometry for the FEM analysis was designed following the technical drawing of a real door, supplied by a company producing naval fire door. The numerical model was validated using a RINA (Registro Navale Italiano) test report [11] regarding the fire-resistant test performed on the door containing the rock wool as an insulator.

2. Component description and fire test

The door examined in this work is a single leaf door with a clear opening of 1200 mm and a height of 2223 mm. The leaf, having dimensions of 1248 mm width and 2250 mm height, is composed of two carbon steel sheets with a thickness of 1 mm containing the insulating material with a thickness of 40 mm. The door frame, consisting of steel profile having thickness of 4 mm, is screwed on the bulkhead by screws with a pitch of 150 mm. The door is fixed to the frame by means of three hinges on the left side and on the right side there is the lock. Figure 1 reports the model geometry obtained from the technical drawing of the door.

The laboratory test procedure is described in the FTP Code.

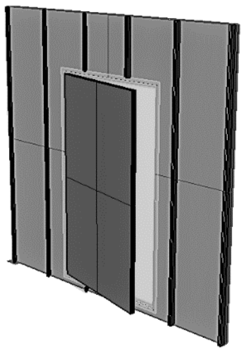

Figure 1. Fire door's model geometry.

In this work, A-60 class door is considered and the fire test is carried out up to 950 °C after 60 min. The test procedure requires temperatures and displacement to be monitored; the temperatures on the unexposed surface should not exceed a defined value and only small gaps between the door and the frame are tolerated since no flame must pass through the door. In Figure 2 the thermocouples positions (1, 2, 3, 4, 5) and the displacements measurement points (A, B, C, D, I) are reported.

The numerical modelling of the fire test requires two steps: a thermal analysis to evaluate the temperature distribution, used as input for a subsequent structural analysis. The thermal and mechanical properties (e.g. thermal conductivity, Young's modulus, etc.) of carbon steel and rock wool (150 kg m^{-3} density) needed for the numerical analysis are tabulated on the supplier's material datasheets for low temperature and integrated with data available in literature for high temperatures [12,13]. The characteristics of innovative foam are evaluated experimentally.

3. Characterization of the innovative insulation foam

The foam is composed of fiberglass scrap grinded and mixed with a biopolymer: it has an open cell structure with fiberglass powders incorporated inside the cell walls constituted by the biopolymer [14]. Figure 3(a) shows a foam sample and Figure 3(b) reports its microstructure acquired with an electronic scanning microscope (SEM).

The foam could have variable density. In this work it is chosen a density of 130 kg m^{-3}.

The compression modulus is evaluated using a Schimadzu AGS-X equipped with a load cell of 10 kN, in accordance with ASTM D1621. The modulus is 3.4 MPa with a standard deviation of 0.1.

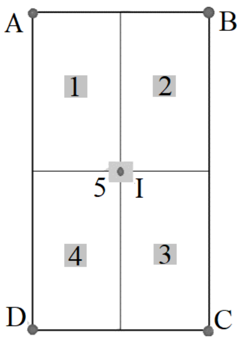

Figure 2. Thermocouples and displacements measurement points.

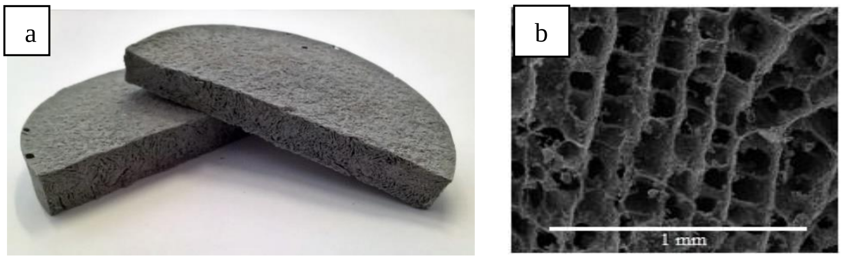

Figure 3. (a) fiberglass foam; (b) fiberglass foam microstructure.

The thermal conductivity from 20 to 80 °C is evaluated with a heat flow meter Netzsch HFM 446 Lambda Small, in accordance with the ASTMC518. The thermal conductivity at 20 °C is 0.045 W (m K)$^{-1}$. Data for the high temperatures are calculated using the theoretical equation expressed in the ISO 10456.

4. Numerical model

FEM analysis is performed using the software Patran with Nastran 2017.

The insulating material is modelled with solid elements, whereas shell elements are adopted for the steel plates of the door, the frame, the bulkhead and the reinforcements.

4.1. Validation of numerical model

A RINA report of a fire test performed on a fire door containing rock wool as insulating material is used to validate the numerical model [11].

For the thermal analysis, instead of carrying out a transient analysis considering the radiation and convection on the face exposed to the fire, a steady-state analysis is performed; the exposed side are subjected directly to the maximum temperature reached after 60 min and equal to 950 °C. As a matter of fact, the time-temperature relationship expressed in the FTP Code (Figure 4) has a low slope after the first few minutes and this consideration allow to perform a steady-state analysis. This simplification permits to reduce the calculation time without losing accuracy in the result, as already demonstrated in the literature [15].

For the unexposed side convection and radiation are considered and an equivalent coefficient of 10 W (m K)$^{-1}$ is applied.

In Figure 5 the temperature distribution obtained after 60 min on the unexposed side of a door containing rock wool is reported.

As required by the FTP Code, temperatures in thermocouples points (Figure 2) are surveyed. Due to the negligible difference between this study results and measurement in RINA reports (Table 1) the model can be considered validated from thermal point of view.

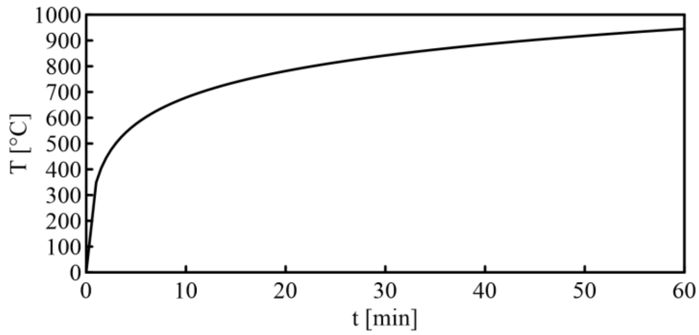

Figure 4. Time-temperature relationship expressed in the FTP Code.

Table 1. Comparison between the temperatures measured after 60 min in the real test and those calculated with the FEM model.

Position	Calculated temperature [°C]	Measured temperature [°C] (RINA Report)	Difference [°C]
1	100	99	+ 1
2	100	100	0
5	99	99	0
3	100	101	- 1
4	100	101	- 1

The bulkhead constraints and the connections between door and frame must be considered for the structural analysis. Since the bulkhead is welded to the test equipment, all translations and rotations at the sides are fixed. Connectors MPC/RBE2 are used to model the lock and the hinges; nodes are forced to have the same displacements. The results show that the leaf, due to the constraints and the internal temperature gradient, tends to inflect in perpendicular direction. Displacements in the other directions can be considered negligible. In Figure 6 the displacement field after 60 min is reported; positive direction is considered towards the fire.

In Table 2 the displacements between door and frame calculated in the measuring points (Figure 2) are reported and compared with data provided by RINA report.

During the real test, it was not possible to measure the displacements in the positions C and D due to the presence of fumes.

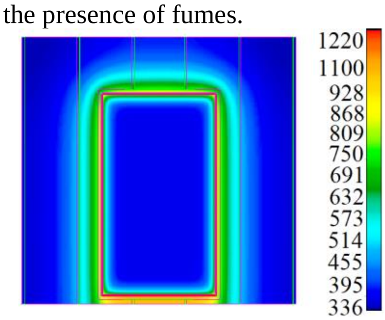

Figure 5. Final temperature distribution expressed in K on the unexposed side of the model with rock wool as insulator.

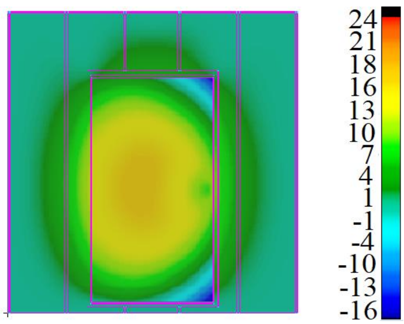

Figure 6. Final displacement field expressed in mm in the perpendicular direction to the model containing the rock wool as insulator.

Table 2. Comparison between the displacements measured after 60 min in the real test and those calculated with the FEM model.

Position	Calculated displacement [mm]	Measured displacement [mm] (RINA Report)	Difference [mm]
A	2	0	+ 2
B	19	19	0
C	18	-	/
D	0	-	/
I	17	17	0

Since the differences between calculated and measured displacement are small, the model can be considered validated also from structural point of view.

4.2. Numerical model with the innovative insulation foam

After the validation process, described in the previous section, the model is applied to simulate the performance of the door with the innovative foam. All the boundary conditions have been kept constant and the insulating materials characteristics have been changed with the innovative foam values. In Figure 7 the temperature distribution after 60 min on the unexposed side is reported.

In Table 3 temperatures surveyed on the model with the innovative foam as insulator are reported and compared with those obtained from the model with rock wool.

Table 3. Comparison between the final temperatures calculated with the model containing the rock wool as insulator and those calculated with the model containing the innovative foam.

Position	Fiberglass model temperature [°C]	Rock wool model temperature [°C]	Difference [°C]
1	120	100	20
2	120	100	20
5	119	99	20
3	120	100	20
4	120	100	20

The increase in temperature is due to the higher thermal conductivity of the innovative foam than rock wool; 0.045 and 0.035 W (m K)$^{-1}$ at 20 °C respectively. Anyway, the FTP Code requirements are satisfied by the model with the innovative insulator.

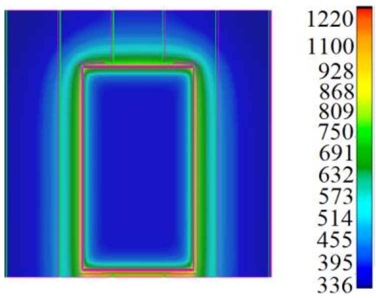

Figure 7. Final temperature distribution expressed in K on the unexposed side of the model with innovative foam as insulator.

From the structural point of view, the substitution of the insulator with the innovative foam do not changes displacement values since the increase of 20 °C of the thermal load does not generate further deformations of the steel.

5. Acoustic properties

The sound absorption analysis is performed with a Kundt tube with a diameter of 45 mm, according to ISO 10534. The sound absorption coefficient (α) indicates sound fraction absorbed by the material; it is the ratio between the absorbed sound intensity and the incident sound intensity. Figure 8 reports the sound absorption coefficient of the foam compared with the rock wool; samples of same thickness (11 mm) are considered.

Frequencies lower than 100 Hz are not reported since their absorption strongly depends on sample thickness and results are not significant. It can be noted that in the medium-high frequency range the sound absorption of the innovative foam is higher than rock wool. This behaviour is related to the different porous structure of the materials; the foam has an open cell structure, while the rock wool is fibrous.

6. Conclusion

The present work highlights the validity of the numerical model realized for the simulation of the fire-resistant test required by FTP Code for fire doors. Furthermore, it shows how it is possible to reduce the computational burden by simplifying the boundary conditions, while providing reliable results.

The FEM analysis demonstrates that the innovative foam can replace the rock wool in A-60 class fire doors. It usage leads to advantages from the environmental point of view and for the operators' health; it allows the reuse of the fiberglass; the production process uses only natural reagents and does not involve the emission of harmful gases and it does not release fibers if handled. Moreover, the innovative foam shows higher acoustic properties than the rock wool, allowing high comfort on board.

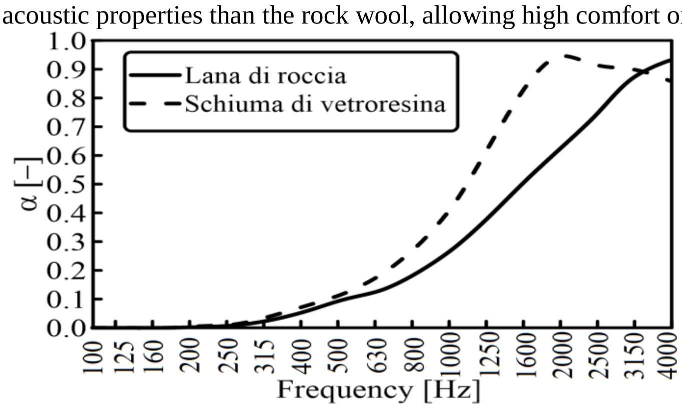

Figure 8. Sound absorption coefficient as a function of frequency for rock wool (continuous line) and innovative foam (dashed line).

As far as the economic aspect is concerned, it is only possible to estimate the cost of the foam, as the production process is still on a laboratory scale. Considering a plant consisting of mill, mixer and freeze-dryer and estimating the need for personnel, the energy consumption and the cost of raw materials based on laboratory experience, a foam cost of 30 € m^{-2} is obtained. It is higher than the cost of the rock wool (4 € m^{-2}), but it should be noted that the production process of the traditional insulator is industrialized and includes economies of scale.

Moreover, despite having a production cost higher than the rock wool, the innovative foam allows to reduce installation costs (equal to 25 € m^{-2} for rock wool, data provided by a manufacturer of naval fire doors): the foam production process allows to produce the insulator with the desired design directly, thus eliminating the whole processing step necessary for the rock wool that is produced in rolls.

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