Mathematical and Computational Applications, Vol. 16, No. 2, pp. 404-413, 2011.

EXPERIMENTAL AND COMPARATIVE STUDY OF DIFFERENT FIBERS ON THE STRENGTH AND FAILURE OF QUASI-ISOTROPIC PLASTIC COMPOSITE WITH A HOLE

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Abstract-In the present study, the effects of different types of fibers on the strength and failure Mechanism of quasi-isotropic silicon carbide/epoxy composite laminate with reinforced hole has been carried out experimentally. The composite panels under compression loadings have been investigated In order to verify the experimental results were compared with the finite element method. A rectangular element with nine nodes has been chosen. Composite plate is meshed into 64 elements and 288 nodes with simply supported and in-plane loading conditions. Two types of reinforcement boundary conditions were investigated; adhesive bonded and snug-fit unbounded plug. For each case, five different sizes of hole diameter were used. And also three different types of reinforcing material (steel, aluminum and E-glass) were employed.

Key Words- Plastic composites, failure mechanism, finite element analysis

1. INTRODUCTION

Plastic matrix composite materials reinforced with metallic fibers are attractive because of their high specific stiffness and strength. Advantage can be taken from the high strength of metallic fibers and the ductility of the metal matrix to produce a composite with superior combined properties. Compared to the conventional materials, the fiber reinforced composite materials presents such distinguished features as high stiffness-to- weight ratio, strength-to-weight ratio and the possibility of changing its stiffness characteristics with keeping its weight constant. Nowadays they are widely used as a primary material in various industrial areas, especially in space and military applications. They offer an increased service temperature and improved specific mechanical properties over existing metal alloys. The investigation of a composite laminate containing a circular hole has been undertaken by several investigators. However, very few studies have been reported for the evaluation of strength for laminate containing circular hole with reinforcement. Kocher and Cross [1] investigated the reinforced cutouts in composite materials. Reinforcements were appeared with the laminate so as to form an integral part of the structure. Tan and Tsai [2] have offered an analytic method which is able to provide the stress distribution near the hole in the laminate. This analytic analysis has shown that the strength of notched laminate can be increased with the proper selection of reinforcement. Pıckett and Sullivan [3] have investigated the reinforcement of hole for very large composite laminates. And also elastic-plastic and residual stresses are very important in failure analysis of plastic matrix Composite materials. When the yield strength of the composite laminate is exceeded, the residual stresses occur in the laminated plates. Lee and Mall [4] have made an experimental investigation about quasi-isotropic epoxy laminate with a hole. The obtained residual stresses can be used to raise the yield strength of the laminated plates. Jeronimidis and Parkyn [5] investigated residual stresses in carbon-fiber/ thermoplastic matrix laminates with hole. Bahaei-El-Din and Dvarak [6] have investigated the elastic-plastic behavior of symmetric metal-matrix composite laminates with holes for the case of in-plane mechanical loading .Karakuzu [7] have given an exact solution to the elasto-plastic stress analysis of an aluminum metal-matrix composite beam reinforced by steel fibers. Residual stresses are determined in metal matrix rotating discs with holes and flat plates containing notches by using finite element method and Tsai-Hill Criterion is used as the failure criterion [8] . An elastic-plastic stress analysis in the steel fibrous aluminum-matrix composites has been made by using the finite element method and the residual stresses have also been found [9,10] .In this paper, the strength and failure mechanism of composite laminates with a reinforced hole have investigated experimentally. Experimental results have been compared with finite element method for only case of steel reinforcing material.

2. MATHEMATICAL FORMULATION

The composite laminated plate of constant thickness is composed of orthotropic layer. Notch geometry and loading configuration is illustrated in Figure 1. The solution of laminated plate includes transverse shear deformations. Therefore, the constitutive relations for an orthotropic composite layer can be written as,

$$\begin{Bmatrix}\sigma_x\\ \sigma_y\\ \tau_{xy}\end{Bmatrix}=\begin{bmatrix}\overline{Q_{11}} & \overline{Q_{12}} & \overline{Q_{16}}\\ \overline{Q_{21}} & \overline{Q_{22}} & \overline{Q_{26}}\\ \overline{Q_{16}} & \overline{Q_{26}} & \overline{Q_{66}}\end{bmatrix}\begin{Bmatrix}\varepsilon_x\\ \varepsilon_y\\ \gamma_{xy}\end{Bmatrix} \quad (1)$$

$$\begin{Bmatrix}\tau_{yz}\\ \tau_{xz}\end{Bmatrix}=\begin{bmatrix}\overline{Q_{44}} & \overline{Q}_{45}\\ \overline{Q}_{45} & \overline{Q_{55}}\end{bmatrix}\begin{Bmatrix}\gamma_{YZ}\\ \gamma_{XZ}\end{Bmatrix}$$

Where the transformed reduced stiffness, $\overline{Q}_{ij}$ are given in terms of engineering constants of the material. According to first-order shear deformation theory, the particles of the plate, originally on a line that is normal to the undeformed middle surface, remain on a straight line during deformation, but this line is not necessarily normal to the deformed middle surface. Thus, the displacement components of a point of coordinates x, y, z for small deformation can be written as follows,

$$u\ (x,y,z) = u_O(x,y) + Z\Psi_x(x,y) \quad (2)$$

v (x,y,z) = v_O (x,y) + Z Ψ_y (x,y)
w (x,y,z) = w (x,y)

where u_O, v_O and w are the displacements of a point on the middle surface, and Ψ_x, Ψ_y are the rotation angles of normal to the y and x axes, respectively.
By using linear strain-displacement relations, bending strains are found to vary linearly through the plate thickness, whereas shear strains are assumed to be constant throughout the thickness as,

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_Y \\ \varepsilon_{xy} \end{Bmatrix} = \begin{Bmatrix} \dfrac{\partial u_0}{\partial x} \\ \dfrac{\partial v_0}{\partial y} \\ \dfrac{\partial u_0}{\partial y} + \dfrac{\partial v_0}{\partial x} \end{Bmatrix} + \begin{Bmatrix} \dfrac{\partial \psi_x}{\partial x} \\ -\dfrac{\partial \psi_y}{\partial y} \\ \dfrac{\partial \psi_x}{\partial y} - \dfrac{\partial \psi_y}{\partial x} \end{Bmatrix} \qquad (3)$$

$$\begin{Bmatrix} \gamma_{yz} \\ \gamma_{xz} \end{Bmatrix} = \begin{vmatrix} \dfrac{\partial w}{\partial y} - \psi_y \\ \dfrac{\partial w}{\partial x} + \psi_x \end{vmatrix}$$

In order to obtain the element equilibrium equations, the total energy of a laminated plate under static loading is given as follows:

$$\Pi = U_b + U_s + V \qquad (4)$$

Where U_b is the strain energy of bending, U_s is the strain energy of shear and V denotes the Potential energy of external in-plane loadings (N_1, N_2, N_{12}).They are defined as,

$$\Pi = \frac{1}{2}\int_{-h/2}^{h/2} [\int_A (\sigma_x\varepsilon_x + \sigma_y\varepsilon_y + \tau_{xy}\gamma_{xy})\, dA]\, dz + \frac{1}{2}\int_{-h/2}^{h/2} [\int_A (\tau_{yz}\gamma_{yz} + \tau_{xz}\gamma_{xz})\, dA]\, dz\ -$$

$$\Pi \int_A Wp\, dA - \int_{\partial R} (N_n^b u_n^0 + N_s^b u_s^0) ds \qquad (5)$$

Where dA = dxdy and R is the region of a rectangle excluding hole, and N_n^b, N_s^b are the in-plane loads applied on the boundary ∂R.The resultant forces N_x ,N_y, N_{xy}, are not constant but are functions of x and y.The forces (N_x ,N_y, N_{xy}), moments M_x, M_y and M_{xy} and shearing forces Q_x and Q_y per unit length of the cross section of the laminated plate are given as,

$$\begin{vmatrix} N_x & M_x \\ N_y & M_y \\ N_{xy} & M_{xy} \end{vmatrix} = \int_{-h/2}^{h/2} \begin{Bmatrix} \sigma_x \\ \sigma_Y \\ \tau_{xy} \end{Bmatrix} (1, z)\, dz \qquad (6)$$

$$\begin{Bmatrix} Q_x \\ Q_y \end{Bmatrix} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \begin{Bmatrix} \tau_{xz} \\ \tau_{yz} \end{Bmatrix} dz$$

For equilibrium, the potential energy Π must be stationary. It is obtained so that $\delta\Pi = 0$ which may be regarded as the principle of virtual displacement for the plate element [10].

3. FINITE ELEMENT ANALYSIS

In this work, finite element procedure is employed to calculate the notched strength and unnotched strength of the composite laminates. Nine-node elements are used with displacement functions. The stiffness matrix of the composite plate can be obtained by using the minimum potential energy principle. Bending and shear and geometric stiffness matrices are,

$$|K_b| = \int_A |B_b|^T |D_b| |B_b|\, dA$$

$$|K_s| = \int_A |B_s|^T |D_s| |B_s|\, dA \qquad (7)$$

$$|K_g| = \int_A |B_g|^T |D_g| |B_g|\, dA$$

where,

$$|D_b| = \begin{vmatrix} A_{ij} & B_{ij} \\ B_{ij} & D_{ij} \end{vmatrix}, \quad |D_s| = \begin{vmatrix} K_1^2 A_{44} & 0 \\ 0 & K_2^2 A_{55} \end{vmatrix}, \quad |D_g| = \begin{vmatrix} \underline{N}_1 & \underline{N}_{12} \\ \overline{N}_{12} & \overline{N}_2 \end{vmatrix}$$

$$(A_{ij}, B_{ij}, D_{ij}) = \int_{-h/2}^{h/2} Q_{ij}\, (1, z, z^2)\, dz, \; (i, j = 1, 2, 6) \qquad (8)$$

$$(A_{44}, A_{55}) = \int_{-h/2}^{h/2} (Q_{44}, Q_{55})\, dz$$

D_b, D_s and D_g are the bending and shear and geometric parts of the material matrix, respectively.
A_{45} is negligible in comparison with A_{44} and A_{55}. K_{55} represents the shear correction factors for rectangular cross-sections and are given as $k_1^2 = k_2^2 = 5/6$.
In order to obtain system equations, the total potential energy principle is used as follows:

$$\delta\Pi = \sum \frac{\partial \Pi}{\delta \Delta p} \cdot \delta \Delta p = 0 \qquad (9)$$

where Π is given by,

$$\Pi = \tfrac{1}{2} \{\Delta\}^T (|K_b| + |K_s| + |K_s| + |K_g|) \{\Delta\} = \tfrac{1}{2} \{\Delta\}^T (|K^*| - \lambda_b |K_b^*|) \{\Delta\} \qquad (10)$$

where,

$$|K^*| = |K_b| + |K_s| - \lambda_b \, |K_g^*| = |K_g|, \quad \lambda_b = -\frac{\overline{N_1}}{N_1^b} = -\frac{\overline{N_2}}{N_2^b} = -\frac{\overline{N_{12}}}{N_{12}^b} \qquad (11)$$

In equation (10), nodal displacements $\{\delta_j\}$ (j = 1, 2, 3 ...n) have been replaced by the global nodal displacement $\{\Delta\}$ whose number of degrees of freedom is nd. From equations (9) and (10), the following linear algebraic equation is obtained,

$$|(|K^*| - \lambda_b |K_b^*|) \{\Delta\}| = 0 \qquad (12)$$

The critical load N_{cr} is obtained from the smallest value eigen λ_b determined by the following equation [9], Det $(|K^*| - \lambda_b |K_g^*|) = 0$ (13)

Equation (13) is solved by using the iteration technique. In this solution, 288 nodes and 64 nine node plate elements are used. Boundary conditions for finite element analysis are illustrated in Figure 2.

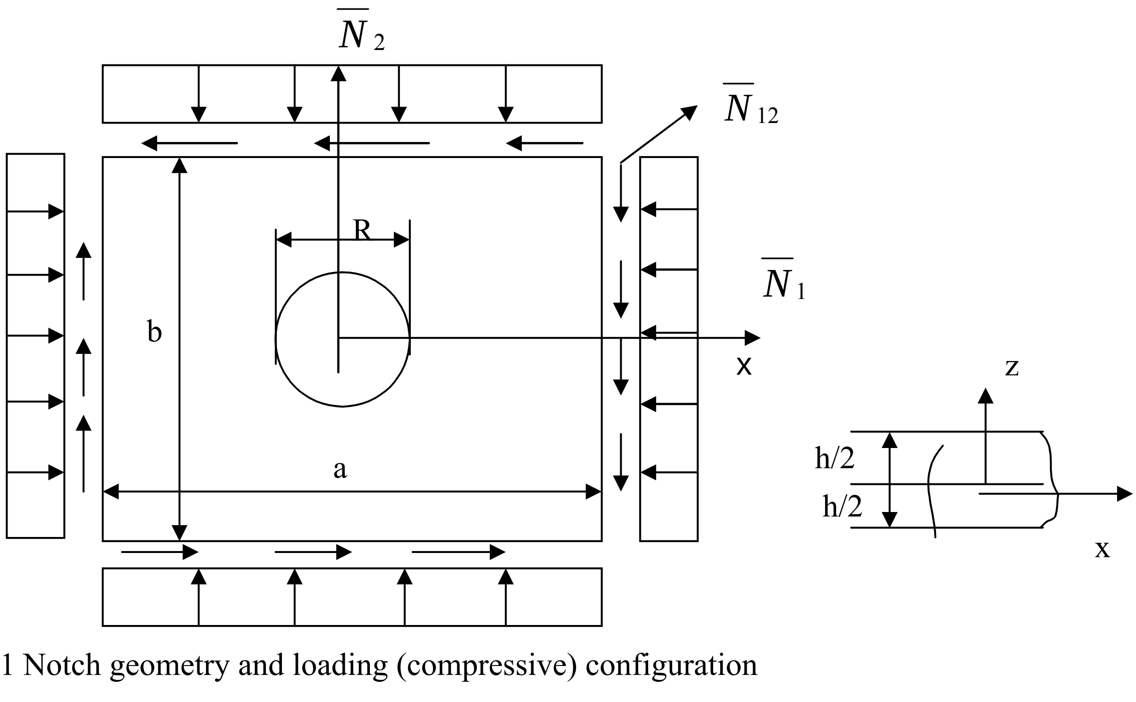

Figure 1 Notch geometry and loading (compressive) configuration

4. EXPERIMENTS

The aim of the experimental study was to research the effects of the following parameters on the strength of plastic composite laminate with a reinforced hole.

Type of reinforcement	1.Adhesively bonded plug 2.snug-fit plug

Material of reinforcement	1.Steel 2.Aluminum 3.E-glass

Five different diameters for hole sizes	1. 2.5 mm 2. 5 mm 3. 7.5 mm 4. 10 mm 5. 12.5 mm

Material features: The material selected for the experiment was silicon carbide/epoxy composite of quasi-isotropic lay-up of $[0/+45/-45/90]_{2s}$ .The thickness of the composite was 2 mm. In order to inspection to effect of material of reinforcement three materials were used. Each material has different stiffness. The widths of specimens were 25 mm. for 2.5 mm and 5 mm. hole diameters and 4 mm. for 7.5 mm. And 10 mm. and 12.5 mm. Hole diameters. The holes in specimens were drilled at the specimen center. Mechanical properties of composite materials used are given in table 1.

Table 1 Mechanical properties of the composite with reinforcing material

	E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	υ_{12}	X_c (Longitudinal compressive strength) (MPa)	Y_c (Transverse compressive strength) (MPa)
Steel	3155	2128	302	0.3	1440	228
Aluminum	204	118	41	0.27	1080	196
E-glass	49.58	18.7	14.5	0.26	620	128

Experimental arrangement: Gage length of compression specimen was selected as 100 mm to prevent buckling. The end tabs were 45 mm. for compression specimens. 0.1 mm. Clearance between plug and hole was selected for good bond between plug and composite. The adhesive EA 9300 was used for reinforcement in the hole. The bonding procedure involved the standard steps of surface preparation and curing at room temperature for six days. The plug length was selected 5 times the thickness of layer for compression. Compression tests were realized in Instron test machine at cross-head speed of 0.5 mm per minute. A typical test involved the testing of composite until complete failure occurred. Initially compression tests of unnotched and open hole specimens were conducted to obtain the date for comparison with the results of reinforced hole specimens. Tests with unbounded and bonded reinforcement were conducted. In case of unbounded reinforcement, it was very important to maintain the maximum contact between plug and hole. To do this it is necessary to make the same size of plug as hole as possible .The results of all compression tests have been stated in terms of Notched Strength Factor , NSF which is defined as:

$$NSF = \frac{\text{Notched strength}}{\text{Un-notched strength}}$$

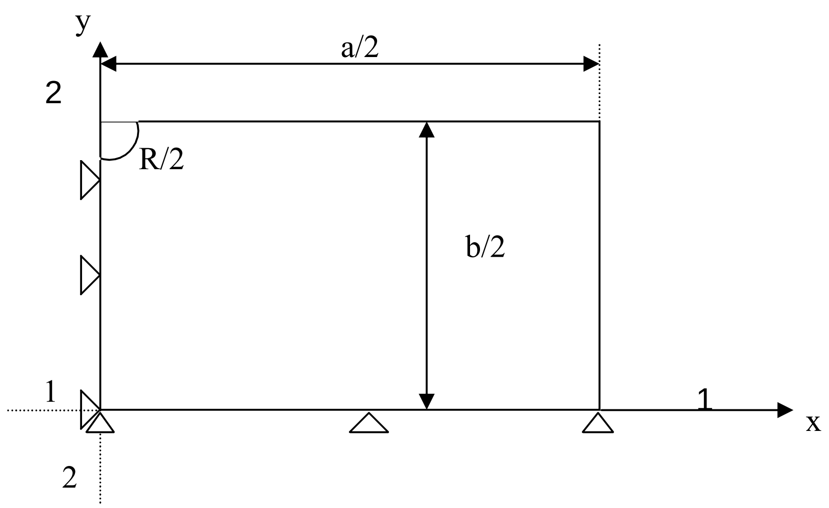

Figure 2. Boundary conditions for the finite element analysis.

5. RESULTS AND DISCUSSIONS

Initially Finite Element Method has been used to develop the data base for comparison with the results of experimental tests. Thereafter, tests with unbounded and bonded reinforcement were conducted which are discussed separately in the following.

Unbounded reinforcement:

Compression loading:

For aluminum reinforced case, improvement in the strength for open hole case was good. This good improvement of strength was for the hole of diameter greater than 5 mm. But, for 2.5 mm hole diameter there was no such improvement. In case of E-glass reinforcement the improvement was relatively small. It may be that the stiffness of E-glass is very much low in comparison to laminated plate .For that reason in most cases the E-glass Reinforcement fractured at same time when the laminated plate failed. In case of steel, the results of test showed that improvement in the strength for 2.5 mm and 5 mm of hole diameters showed similar results as in case of aluminum. But for the case of larger hole, it showed less increase than aluminum. The stiffness of steel is much higher than that of laminated plate. That is why it did not follow the deformed shape of laminated plate hole with increase of the load. The results of all compression tests are shown in figure 3. It can be seen from figure 3. The improvement of steel reinforcement showed large amount as in aluminum case.

Bounded reinforcement:

Compression tests:

The compression test with bonded reinforcement was realized with two types of reinforcement which were steel and aluminum. The results of this case are shown in Figure 4 for comparison. It can easy seen that the improvement in strength due to reinforcement in comparison to open or unreinforced hole which is very similar to its counterpart with unbounded reinforcement. The increase in strength was very much in case of bonded reinforcement than unbounded reinforcement for both aluminum and steel. However, bonded aluminum of large diameter significantly improved in strength in comparison to open hole.

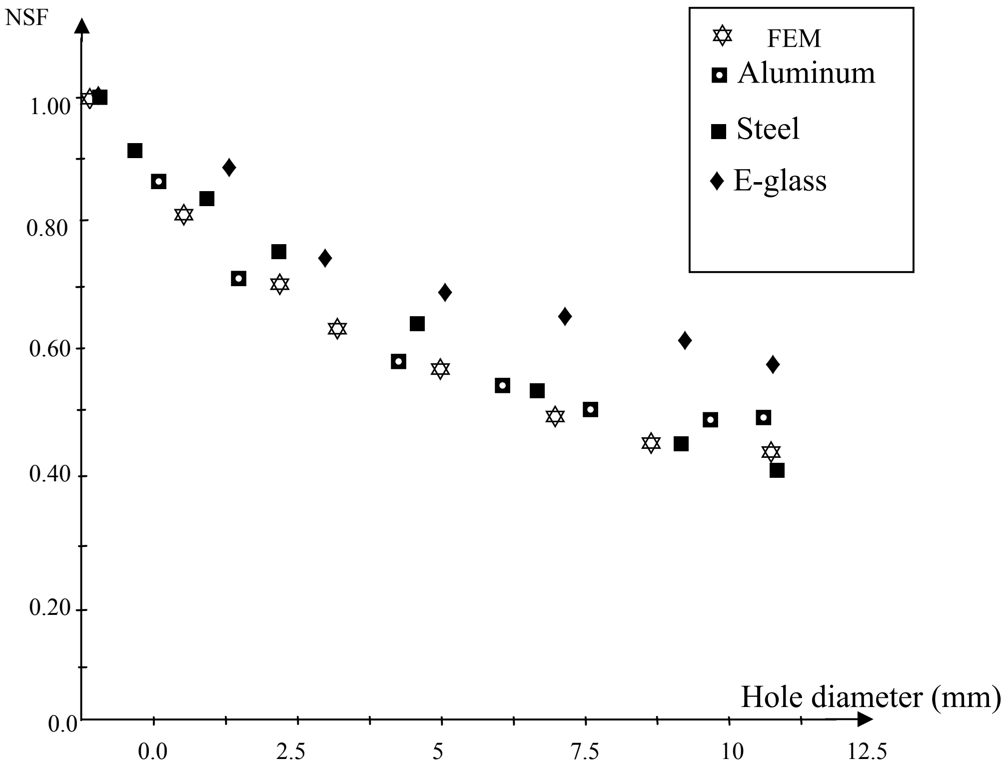

Figure 3 Comparison of NSF for unbounded reinforcements. (FEM only for steel)

6. CONCLUSION

In the present study, the effects of different types of fibers on the strength and failure mechanism of quasi-isotropic silicon carbide/epoxy composite laminate with reinforced hole have been investigated experimentally. The tested composite laminated plate with a reinforced hole showed improvement of ultimate strength relative to the laminate with open hole. The largest improvement was obtained with the reinforcing material having same stiffness as that of laminate. This improvement was also related to the size of reinforcement. Further, the improvement in the strength is related due to more much interaction between hole and reinforcing plug during loading.

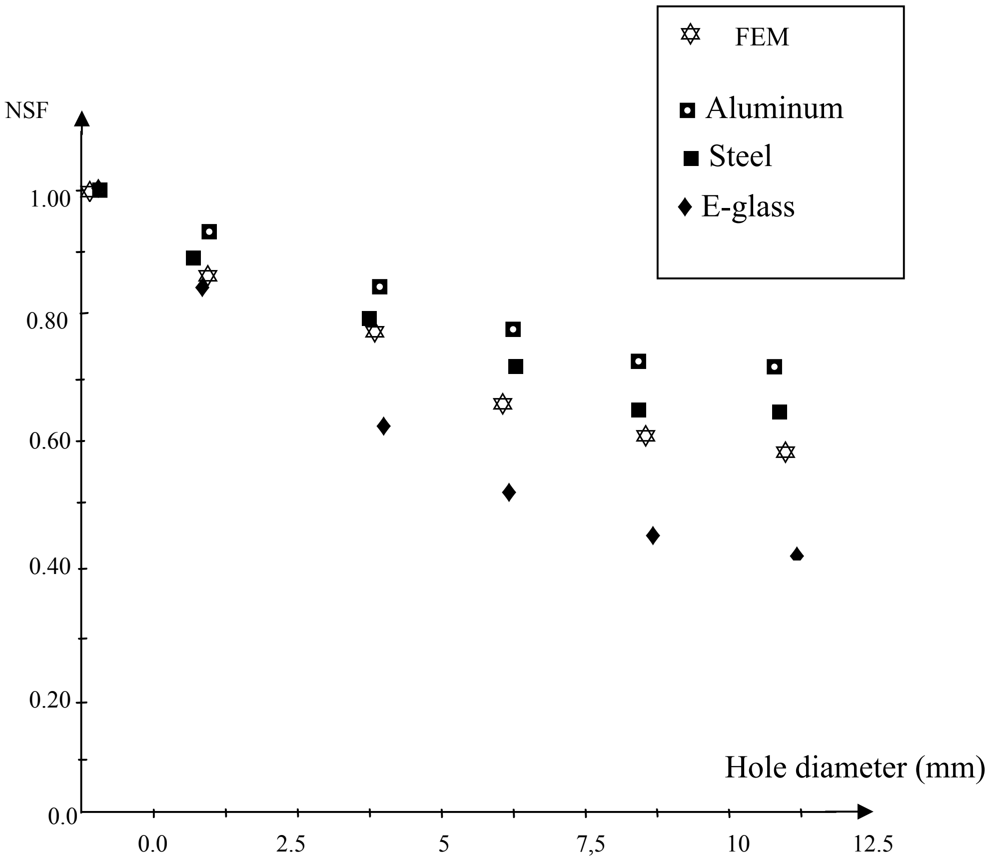

Figure 4 Comparison of NSF for bounded reinforcements.

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