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Design of an under-bonnet heat exchanger for the improvement of energy efficiency

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Abstract

The present work is aimed at reporting the methodology used to develop an innovative type of heat exchanger to exploit the free space under the upper skin of a car bonnet between the stiffener ribs. The idea is to take advantage of the large surface of the bonnet itself as a radiating area to increase the heat exchange capacity of the cooling system to save energy and improve the overall vehicle efficiency. The heat exchanger can be built with a thin-shell under-bonnet properly shaped that, fixed below the lower surface of the bonnet skin, realizes a closed chamber where the cooling fluid can pass and exchange heat. With the aim of weight reduction, the thin-shell under-bonnet will be made of plastic material and the technology to fix it and create the closed chamber will be, necessarily, structural bonding. To this aim, it has been necessary to develop a methodology to characterize the metal-to-plastic adhesive joint to design and verify the proposed solution. In the work, the experimental method consisting of a C-shaped metal half-specimen (made of steel, and obtained from a sample of a vehicle bonnet) on a plastic plate of the material used for the thin-shell under-bonnet will be illustrated. The adhesion properties of the joint have been then obtained by means of the inverse method with a parametric numerical model reproducing in detail the experimental test in order to identify the parameters of the material model used to describe the adhesive behavior. The necessity of this type of test depends on the type of applied load, mainly direct pull-out, and the type of joined parts and materials. Once the adhesive model parameters obtained, they have been used to virtually study a prototype of the heat exchanger to obtain a suitable solution in terms of thermo-mechanical strength and energetic efficiency.

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1. Introduction

The heat generated by internal combustion engines (ICE) is almost always dissipated through a front radiator, which is a heat exchanger mounted in the front part of the vehicle where cooler air exchanges heat mainly by convection. It is a simple design already present in car as old as the Pahnard-Levassor model of 1889, see Gregersen (2011), and very effective being placed in its ideal position receiving a great airflow at least when moving forward. However, it introduces some design constraint not always appreciated in modern vehicles. Additionally, in modern designs where a large longitudinal gap is left between the front structure, carrying the radiator, and the front end, with the front beam and the bumper, the airflow is altered and not always efficient. For this reason, forced ventilation is often necessary. However, forced ventilation requires power with a negative downside in terms of energy management and reduction of consumption and pollution.

Solutions are found improving the heat exchange of the cooling system by adopting innovative designs or more suitable materials for its components. An obvious solution is to increase the area where heat exchange occurs. Adding more heat exchanging devices is a way to perform this task. Of course, this can be done where the car is interested to the direct contact with the outer space and airflow. This means the external surfaces; nevertheless, not all external surfaces can be made available for this purpose both because of aesthetic constraints or functional limitations. On the contrary, under-floor and under-bonnet areas can be exploited to some extent. The present work deals with the design of such component under the car bonnet in the free area between the typical ribs which provide the required stiffness and strength of the bonnet itself. This area is not very large but enough to contribute to the overall objective. The heat exchange will occur between the cooling fluid and the airflow over the bonnet through the metal sheet. Anyhow, the cooling fluid must be contained and this can be obtained by creating a closed chamber where one wall is the bonnet and the other half is the part joined together. The material selection and the shape of this second part is the purpose of the work as well as the way to join it to the bonnet.

This work describes the method used to design the connection between the two parts of the heat exchanger. This includes, after a preliminary selection of the materials suitable for the heat exchanger construction: the characterization of the materials, the characterization of suitable joining technologies to assemble the parts, and, finally, the design of the proposed prototype.

2. Materials

The design process of innovative under-bonnet heat exchanger must start from the materials selection. Obviously, requirements and constraints are the crucial guidelines in this part of the study. The heat exchanger features three main components: the car bonnet, the under-bonnet shell and the adhesive. The bonnet itself represents the first constraint, indeed the bonnet is made, as in most solutions in the car sector, in a typical steel for metal forming. Since a commercial solution was considered, the exact type of steel is not exactly known. On the other hand, the adhesive and the shell have to be carefully selected taking care of their structural strength and overall weight.

2.1. *Plastics*

Polymeric materials well suit in industrial applications where relative high mechanical/thermal strength and complicated geometries are required. Moreover, due to the particular shape and size to satisfy, thermoforming is the most suitable manufacturing process to take into account. Among all the possible thermoplastics, ABS and Bayblend (more specifically, a polymeric blend of ABS/PC) were considered the most suitable for the application because guarantee the mechanical and thermal strength and processability. In addition, these materials are relatively cheaper with respect special plastics with similar properties.

The refrigerating liquid in the under-bonnet heat exchanger is a mixture of ethylene glycol and water 50%/50%. To test the compatibility of the glycol mixture with the polymers, samples of the two materials were produced and tested in an ageing environment. The test consists of immersing the specimen in the glycol mixture keeping the

temperature at 80 °C, which is the maximum admissible temperature of the refrigerating liquid in the cooling system, and measuring the average weight increase weekly. Specimens, made by injection molding in a hydraulic press, have prismatic shape with a rectangular cross-section 3×6.5 mm and length of 60 mm. For ageing tests 10 samples of Bayblend and ABS were produced. ABS got an average weight increase of 0.35% after one week, then 0.1% weekly. After 8 weeks, the total average weekly increase was still of 0.08% so that the final increase was of 0.48%. For Bayblend the average initial increase after one week, again calculated as the average of 10 samples, was equal to 0.32%, slightly less than for ABS. The weekly increase after the first was of 0.04%, even after two months. The total average with respect to the *tel quel* samples was of 0.08% as for ABS. However, the final increase in weight was only 0.40% which can be considered acceptable for the intended application.

The result of the aging tests confirms the compatibility of both materials in that application; nevertheless, their mechanical behavior is a crucial information to take into account to select one of them. For this reason, static tensile tests on prismatic specimens (45 mm×6.5 mm×3.1 mm) were carried out. In order to study the effect of the aging on the material response, tensile tests were performed on non-aged and aged samples. Results of the tensile tests are reported in Fig. 1.

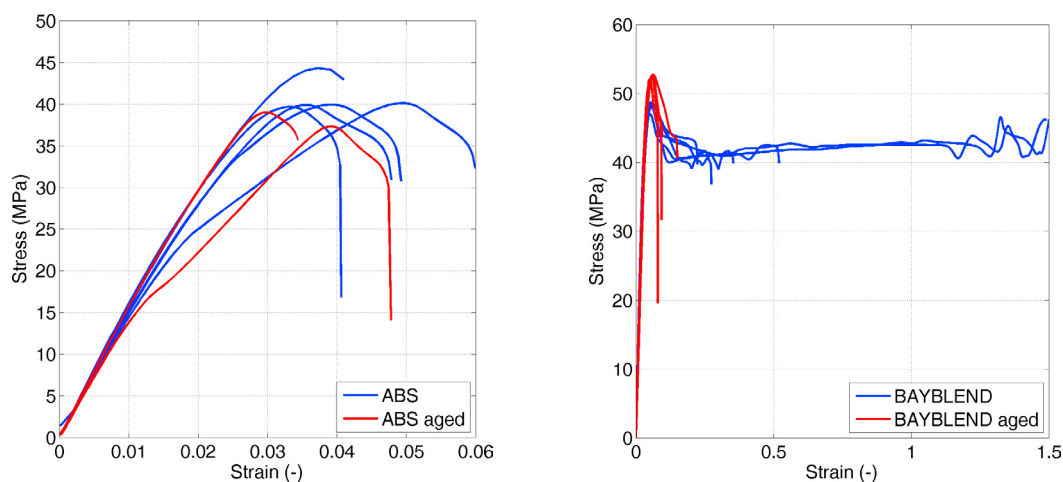


Fig. 1. Results of the tensile tests on the substrate materials: *left*) ABS and *right*) Bayblend.

The first important observation is about the effect of the ageing on the mechanical behavior of Bayblend; indeed, after the ageing in the glycol mixture, the elongation at failure is dramatically reduced inducing an almost brittle behavior to the material. However, the influence is not on strength, which is even increased after aging. ABS, on the contrary, shows brittle behavior, but it is not really affected by ageing. Comparing the two polymers, in equal conditions, Bayblend shows higher elongation and strength.

Creep tests were also performed in order to observe any other important discrepancy between the two materials. Tests were performed in a three-double cantilever arrangement by using the same tensile specimens. The bending stress was set at 2 MPa at the temperature at 80 °C. After 70 hours, ABS cumulated a total strain of 0.6%, which is much lower than 2.1% shown by Bayblend. This last result highlights a remarkable difference in the behavior of the two polymers and, considering the previous results, the ABS generally shows higher resistance and aging stability with respect Bayblend.

2.2. Adhesives

The adhesive bonding of the plastic component to the lower surface of the bonnet represents a crucial point of the heat exchanger design. Thermal and mechanical strengths are the keystones to take into account for the selection of the adhesive. Suitable candidates were compared starting from the data-sheets of several commercial adhesives. Even if there are many solutions valid in terms of thermal strength, the mechanical strength of the polymeric-metal joint is

often unknown and in general weaker than the metal-metal adhesion. Nevertheless, three solutions were found in terms of mechanical/thermal strength, bonding compatibility and loading mode of the adhesive joint. The adhesives selected, all provided by Henkel, are:

- Loctite UK 1351 B25 (polyurethane, two-components, green, fixture time 75 minutes);
- Teroson MS 9399 (silane-modified polymer, two-components, black, processing time 2.5-3 hours);
- Terokal 5055 (epoxy resin, two-components, black, full hardening time 1 week).

The polyurethane adhesive, shorten *PU*, has a medium hazard index due to the presence of isocyanates, but a good expected shear strength of 14 MPa (measured in single lap-shear test according to ISO 4587, after curing at room temperature for 1 week or 6-8 hours at 40 °C). The modified silicone polymer, shorten *MS*, has the advantage of a greater deformability but a much lower strength of only 2 MPa and possible degradation from 90 °C, which could be a problem in the current application. The epoxy resin, shorten *EP*, has a shear strength comparable with the polyurethane (18-22 MPa) and a high impact strength.

Samples of the three adhesives were subjected to the aging test as described for the polymeric substrate materials. *MS* and *EP* shown a weight increment of 9.72% and 18.35% respectively after two weeks, which progressively decreased up to 1.21% and 14.88% respectively after two months. On the contrary, *PU* shown a relevant weight decrease after two weeks, 5.93%, which slightly went back to 3.57% after two months. These quite large variations can be, anyway, accepted due to the fact that the adhesives have a very small thickness, so the overall changes remain negligible. In addition, mostly critical was the behavior of the *PU* suffering of large shape distortion; instead, *EP* became extremely flexible.

Tensile tests were also performed on aged and non-aged samples of the adhesives in order to evaluate the bulk material properties. Results are reported in Fig. 2.

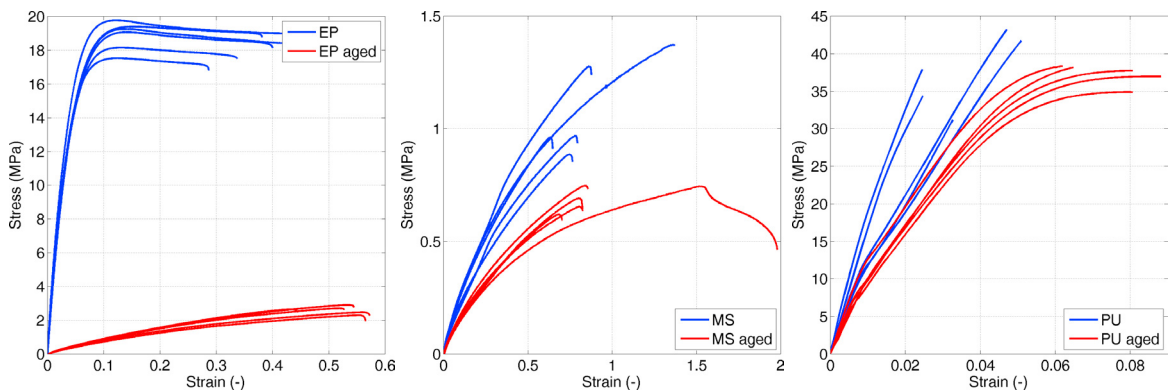


Fig. 2. Results of the tensile tests on the adhesives: *left*) EP, *center*) MS and *right*) PU.

From the obtained results, it is evident that EP adhesive is mostly affected by ageing in the glycol mixture. Even if elongation at failure remains almost unmodified, the strength is strongly reduced of one order of magnitude, making this material probably disadvantageous for the current application. On the contrary, MS and PU are not really affected by the aging; nevertheless, the results confirm the weakness of MS in strength and its high deformability. These results are very important in order to observe any drastic change in the material behavior after aging, but they are not enough for selecting the adhesive since the bonding strength is the most important parameter to take into account in polymeric-metal joint.

3. Characterization of the adhesive joint

3.1. Experimental setup

To characterize the bonding strength, a specific mechanical test was designed for this purpose. The test setup was realized in order to reproduce as much as possible the real joint condition. In the under-bonnet heat exchanger, the plastic half-shell has to be bonded to the lower surface of the bonnet itself, then the pressure load will generate a load normal to the bonded surface inducing an opening load on the adhesive. This tearing off mode cannot be evaluated efficiently by standard tests such as ASTM D1002 - 10, D1062 - 08 (2015), or D903 - 98(2010) which are for metals, as for example done by Peroni et al. (2009), Avalle et al. (2010) or Scattina et al. (2011); and not even ASTM D3163 - 01 (2014), D3164 - 03 (2017), or D3807 - 98 (2012) which are for plastics, especially because of the nature of the problem where two extremely dissimilar materials are joined. Both due to the manufacturing process and materials properties, the standard tests are not easily adaptable to this specific case and loading mode.

In the dedicated test stand, the bonding resistance is evaluated tearing off a metal U-shaped specimen, like the type used in the KS2 method in Zhang (2001), Avalle (2004), Peroni et al. (2006), Feucht et al. (2007), representing the bonnet side, from a polymeric flat plate, representing the plastic half-shell. The two parts are joined by means of the adhesive, which undergoes a constant load in normal direction with respect to the bonded surface, Fig. 3.

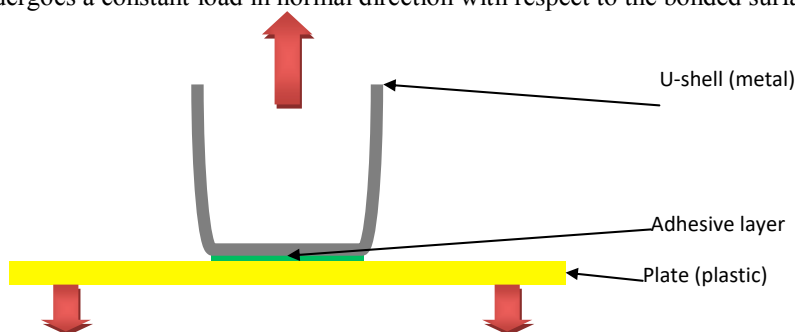


Fig. 3. Test method for the evaluation of the strength of the bonded joint.

The shape of the two components were also chosen taking into account the manufacturing process. The plastic plate is a square of 135 mm side with a thickness of 5 mm, which can be produced by injection molding or, like in this case, by pressure molding. The U-shaped metal sample has a square base (bonded to the plastic plate) of 15 mm edge and two lateral extensions of 20 mm for clamping. The thickness of the adhesive layer is roughly 1 mm. A universal electromechanical material testing machine (Zwick Z100) was used to perform the tests. The test machine features a maximum load of 100 kN and is equipped with a low capacity load cell to adapt the load to the actual maximum force of the joint. The plastic plate was fixed on the bottom fixture of the test machine by means of four M18 screws as in Fig. 4. The screws were not tightened to avoid pre-stress in the joint due to the unavoidable distortions induced in the plate by holding tightly. The U-shaped shell above was fixed to the moving fixture of the testing machine by means of a properly made couple of side clamps tightened by a couple of bolts.

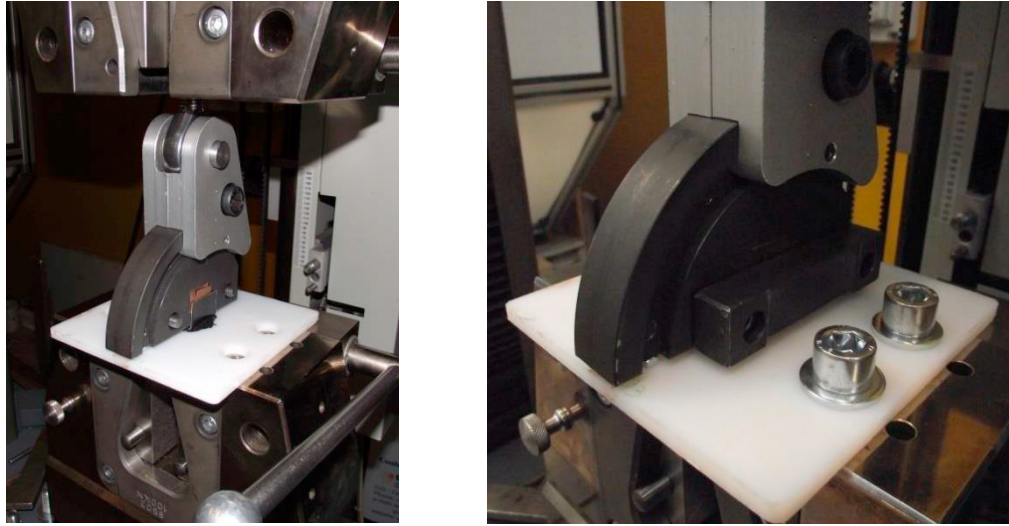


Fig. 4. Experimental test stand: *left*) unclamped and *right*) clamped system.

3.2. Experimental results

Six samples of each combination of the two polymeric substrates (ABS and Bayblend) and of the three adhesives (EP, MS and PU) analyzed before were assembled and tested. A total of 36 samples were tested to find the best joint combination. Results are reported in Fig. 5.

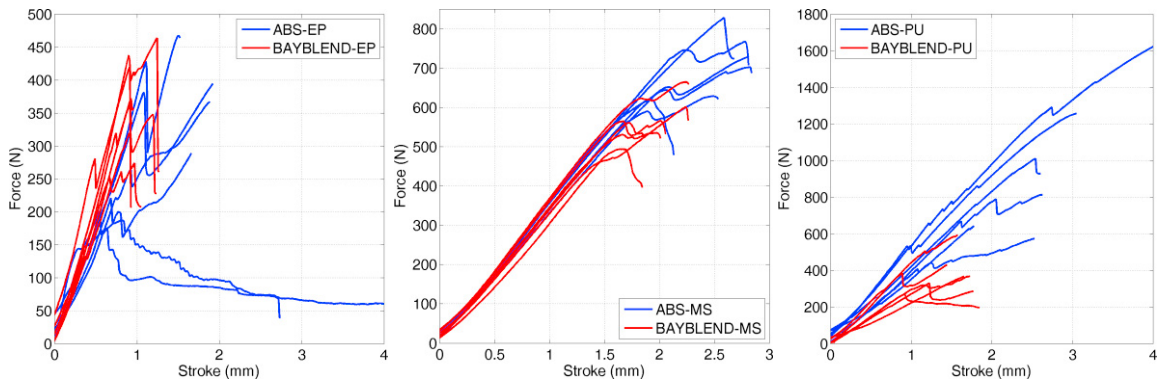


Fig. 5. Adhesively bonded joint tests: *left*) epoxy resin, *center*) silane-modified polymer and *right*) polyurethane adhesive.

At first, it is possible to notice a moderate influence of the substrate materials: for all adhesives, the joining strength is always higher with the ABS, from a moderate influence with EP resin to a significant difference with the PU adhesive. From this point of view, and taking also into account the high sensitivity of Bayblend to the interaction with the refrigerating glycol liquid, it can be concluded that ABS is most interesting polymer to adopt for the under-bonnet heat exchanger. Concerning the adhesives, the MS shown high stability to the aging with respect to the other ones; nevertheless, its mechanical strength is quite weak. Anyway, the maximum expected pressure of the refrigerating liquid in the heat exchanger is 1.6 bar which should be guaranteed by MS. Moreover, MS shown a relative high deformation which could be a crucial positive point taking into account the compensation of the thermal expansion of different materials joined. For these reasons, ABS and silane-modified polymer were selected for this application.

3.3. Identification of the substrates

To model the behavior of the substrate, to be used in the following virtual design phases, a suitable material model has to be selected and calibrated. For ABS the stress-strain relationship, Fig. 1, shows an extended hardening phase followed by irreversible deformation representing the typical plastic behavior. For this reason, the chosen material model is based on a power law describing the plastic flow. This model is relatively simple and typically insufficient to describe the complex behavior of a polymeric material, so that more efficient models were used for example in Peroni et al. (2008) and Avasle et al. (2010), or including visco-elastic effect in Perzyna (1966) or Owen et al. (1992), but from the point of view of the current application it is perfectly suitable to describe the non-linearity of the material. Hence, the relation to be identified is:

$$\sigma_y = k\varepsilon^n \quad (1)$$

Where k and n represent the constants of the plastic work, σ_y is the plastic flow stress, and ε is the effective plastic strain. The model is implemented as MAT_018_POWER_LAW_PLASTICITY in LS-DYNA 9.71, see Hallquist (2006).

The FE model consists of a very simple hexahedron fine mesh used to calibrate and identify the plastic flow law of the tested ABS. The geometry and boundary conditions carefully reflect that of the experimental test. The reference stress-strain curve, used as target for the optimization, was obtained as an average of the experimental tests on the ABS after ageing. An inverse method approach was then used to identify the material parameters by using the LS-OPT program, Stander et al. (2015), to minimize the scatter between the experimental (reference) stress-strain curve and that obtained by simulation while varying the parameters themselves. The global error between the target and the numerical curve is 2.9%. The set of identified parameters for the ABS is reported in Table 1.

Table 1. Parameters of the power law of the ABS polymer.

Parameter (unit)	Value
Elastic modulus, E (GPa)	1.36
Plastic hardening constant, k (MPa)	141.2
Plastic hardening exponent, n (-)	0.39

3.4. Identification of the bonded joint

Exactly as for calibrating the material model of ABS, the parameters set for the adhesive material was performed. The adhesive considered is the MS polymer previously suggested as the best solution for the current application.

In this case the difference is the different experimental test and numerical model used. The experimental test is the previously described tearing test of the U-shaped steel specimen bonded to the polymeric plate. In Fig. 6 the FE model is illustrated: the boundary conditions were reproduced as close as possible to the experimental test conditions.

Fig. 7, instead, reports the optimization target curve which is the averaged load-stroke curve obtained from the experimental tests.

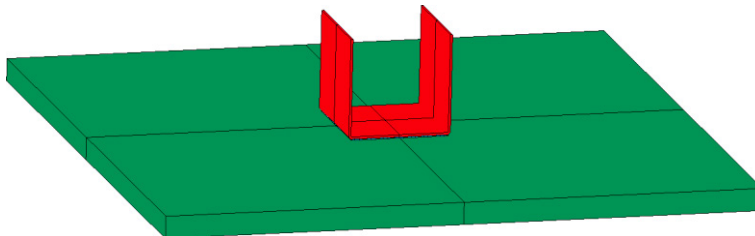


Fig. 6. FE model used for the identification of the material model of the adhesive.

Also for the adhesive a power law was used to describe the plastic flow. For the substrate, the previously identified material model is used, whereas for the metal sheet a power law with the following parameters was used from Kalpakjian et al. (2003): plastic hardening constant $k = 760$ MPa, plastic hardening exponent $n = 0.19$. The total error obtained between the target and the numerical result is 2.8%. The set of identified parameters for the MS polymer adhesive is reported in Table 2.

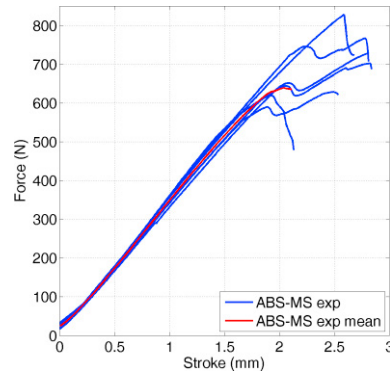


Fig. 7. Experimental load-displacement curves (blue) and optimization target (red).

Table 2. Parameters of the power law of the MS polymer adhesive.

Parameter (unit)	Value
Elastic modulus, E (MPa)	3.30
Plastic hardening constant, k (MPa)	5.25
Plastic hardening exponent, n (-)	0.46

4. Design of the prototype

4.1. Geometry

The final design phase consisted of the virtual analysis by FE simulation of the prototype. The virtual analysis is meant to check the validity of the proposed solution in terms of mechanical strength. Mechanical strength will be evaluated by the capacity to sustain the pressure loading due to the refrigerating (glycol) liquid in the under-bonnet heat exchanger.

The virtual design procedure consists of the definition of the geometrical model, the implementation of the materials models and the numerical simulation of the whole system considering the loading conditions.

The geometrical model of the lower part (polymeric) of the under-bonnet heat exchanger was obtained to be compatible with the space available. In the case of the analyzed application the whole central region of the bonnet is free and, thus, available as area for thermal exchange (about 1.42×10^5 mm²). The lower part of the heat exchanger has been designed from the external geometry of the bonnet itself following the shape of the under-bonnet stiffeners as boundaries for the under-bonnet heat exchanger.

The proposed prototype is shown in Fig. 8 as it appears mounted below the bonnet. In Fig. 9 a detailed top and bottom view is shown. It allows the passage of the liquid flow in a vertical space as large as 10 mm in the vertical direction and extending over almost all the internal area. The total volume of the refrigerating liquid containable in the heat exchanger is 7.3×10^5 mm³. The component is a thermoformed 3 mm thick ABS shell with the maximum longitudinal size of 825 mm and 205 mm in the transversal direction. The contour bonded area has an average width of 20 mm, whereas internal fixation areas (circular) have a diameter of 10 mm. They connect the lower surface of the bonnet to the rest of the ABS shell by means of frustum shaped supports. The fixation area for the frustum shaped supports is 8.9×10^3 mm² and 3.49×10^4 mm² for the contour, which means that 31% of the available free area for heat exchanging is exploited for bonding. Finally, at the sides, 12 mm diameter connections for the entrance and exit of the cooling liquid are provided.



Fig. 8. Proposed prototype of the under-bonnet heat exchanger: both parts, upper part corresponding to the bonnet itself (in red, steel) and lower part (polymeric, in blue; to be bonded to the upper part).

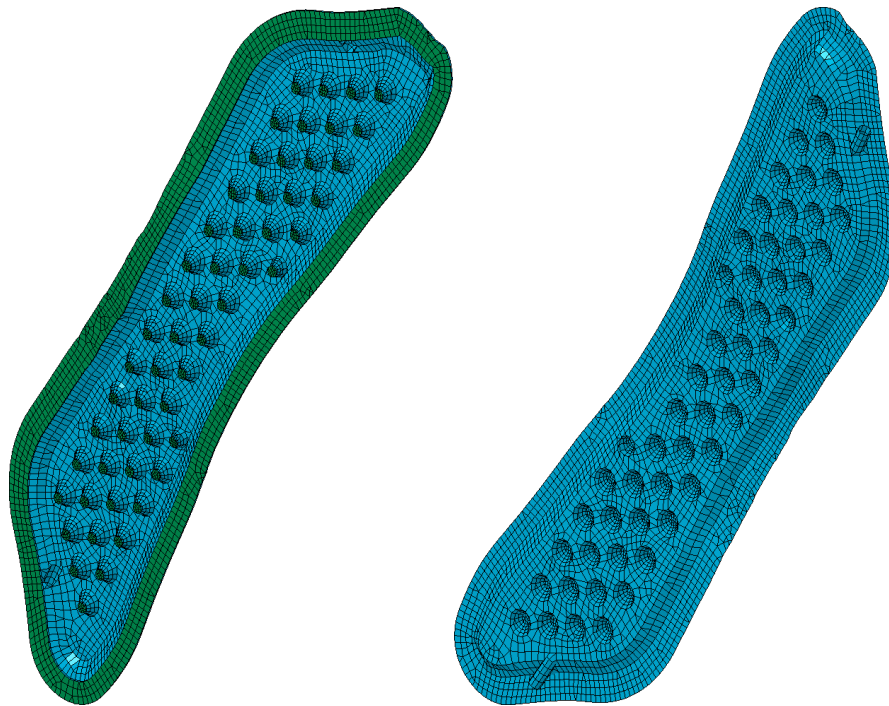


Fig. 9. Top (left) and bottom (right) views of the proposed prototype of the heat exchanger: polymeric shell (blue) and adhesive (green).

4.2. Numerical model

Numerical simulations were performed with the LS-DYNA code. The FE model features of full-integration solid elements for all the parts in the model, namely: the bonnet, the adhesive and the ABS shell of the heat exchanger.

The three identified material models were assigned to the three parts. It is important to note that for the adhesive, a value of the maximum principal strain at failure was identified as 190%, whereas the stress limit was found for an

equivalent Von Mises maximum strength of 2.7 MPa. These values were found during the optimization for the identification of the material models. The Von Mises failure criterion is somewhat quite rough for this polymeric material, and more complex failure models as described for example by Kolling et al. (2005) are available: however, it seems acceptable taking into account the other uncertainties of the design and the limitations in terms of experimental information. Corresponding to reaching the limit in terms of the maximum load, as defined by the optimization target, the maximum values of the principal strain, and the maximum equivalent stress in the model were found. These values were considered at the limit for the adhesive material. For this reason, in the FE model an erosion algorithm was included. This type of algorithm, once one of the limit conditions is met in a single element, erases the element itself from the numerical model. This erosion operation is repeated whenever failure occurs in an element.

Finally, for the sake of simplicity, the bonnet was simply constrained along its entire external boundary, whereas the polymeric shell and the bonnet are bonded by the adhesive by means of a tied contact algorithm. As for the loading, a pressure ramp from 0 to 5 bar over the entire internal surface was applied. This value of the applied pressure is largely over the operating condition of 1 bar; nevertheless, in that way it is possible to study when failure occurs.

The numerical simulation was performed by means of an explicit FE solution. To evaluate the strength of the designed component in sustaining the prescribed pressure, the average internal pressure in the heat exchanger at the occurrence of the failure of the first adhesive element was evaluated. At the onset of failure (elimination) of the first element (due to reaching one of the material limits) the average pressure in the heat exchanger was 1.16 bar.

Concluding, it is possible to say that, from this virtual analysis by numerical FE simulation, the designed under-bonnet heat exchanger is able to sustain the prescribed working pressure with a slight safety margin.

4.3. Thermal simulation

In order to assess the thermal effectiveness of the proposed prototype a thermal simulation was performed. A fluid dynamic analysis was run using the *Computational Fluid Dynamics* (CFD) software embedded in ANSYS. For the sake of simplicity, only the refrigerating liquid was taken into account assuming the air motion over the bonnet at constant temperature, 25 °C, and velocity, 50 km/h. With these conditions, according to requirements, the temperature drop-off of the cooling liquid should be 20 °C at the maximum flow rate of 1200 l/h. The inlet temperature of the refrigerating liquid in the heat exchanger in normal working condition is 80 °C. In Fig. 10 the temperature distribution of the water-glycol mixture is reported. At the outlet point of the heat exchanger, the liquid temperature is approximately 54 °C fulfilling the requirement. In addition, the liquid temperature homogeneously decrease along the heat exchanger and the frustum shaped supports have negligible effect on the liquid flow.

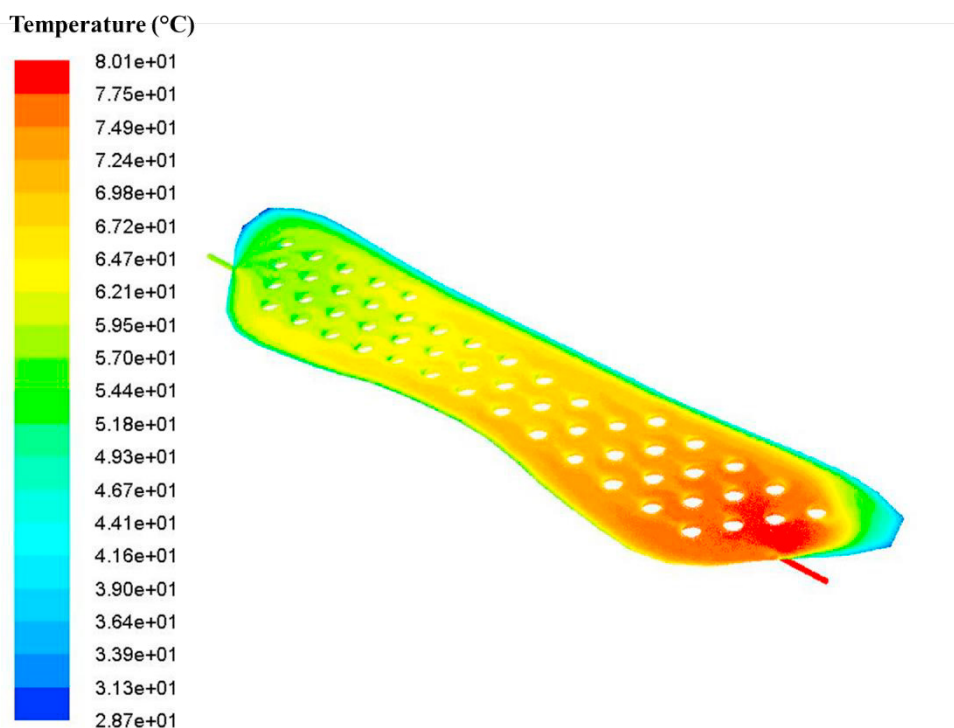


Fig. 10. Temperature distribution of the refrigerating liquid which goes through the heat exchanger assuming air convection at 50 km/h.

5. Conclusions

In the present work a methodology to design a plastic component for exchanging heat under the bonnet of a car was reported. The plastic under-bonnet component had to be bonded under the bonnet itself, therefore, also design criteria for the adhesive joint had to be obtained.

For this aim, experimental tests both on the plastic of the under-bonnet and on the adhesive material were performed. The experimental tests were mechanical and environmental to check compatibility of the materials with the cooling liquid. Different materials were considered and tested to come to a most suitable selection.

Fundamental is the evaluation of the adhesive joint strength: due to the specific mode of load application and the nature of the bonded materials an acceptable standard testing method was not considered to be available. Consequently, a completely new testing procedure was conceived and applied to the examined adhesive joints. This led to the identification of the most suitable adhesive, and of the joint properties for the design.

Finally, a proposed solution for the final component was obtained and verified in terms of strength. The solution was virtually tested and can be considered as a suitable solution for the purpose; moreover, the fluid dynamic analysis confirmed its thermal effectiveness.

Acknowledgements

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