Computer-aided design of new service doors for recreational vehicles

Yary Volpe, Lapo Governi, and Rocco Furferi

Abstract— Recreational vehicles (camper, vans and motorhomes) are equipped with service doors to access to specific areas such as water tank or luggage zone. As the state-of-the-art technology stands at present, two different typologies of service doors are manufactured: doors with plastic frames, obtained by injection molding, and doors with aluminum frames realized by extruded bars. Plastic frame-based doors are characterized by concealed hinges (i.e. hinges integrated in the frame), therefore resulting aesthetically pleasant to the final user. Unfortunately, they are basically produced in standard dimensions due to the complexity and costs of injection molding process; as a consequence the number of available measures in the market is really limited. Quite the reverse, aluminum frame-based doors can be produced in customizable formats by adjusting the bars length. The main drawbacks of this second typology of doors are that the cutting and bending machines, used to produce them, need to be periodically tuned in order to take into account possible environmental thermal variations and, moreover, in order to achieve 180° opening, the hinges are required to stick out the wall. Moving from these considerations, this work proposes a CAD/CAE-based design of an innovative service door based on a modular design where frames consist of extruded plastic bars, cut in required length, which are capable to comprise concealed hinges. Accordingly, the new door designed in the present work brings together the advantages offered by the standard solutions pushing forward the RV door technological state of the art.

Keywords— CAD, CAE, Slam test, service doors

I. Introduction

RECREATIONAL VEHICLE (RV) is the usual term for a motor vehicle equipped with living space and amenities found in a home. This definition covers different types of vehicles such as caravans, camper vans and motorhomes. Whatever the RV type, its walls are always characterized by different kinds of openings such as windows, doors and service doors (see Figure 1).

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Fig. 1 Typical RV openings [1]

With reference to service doors, nowadays, the market proves to be rather homogeneous in realizing two different typologies: 1. doors with plastic frames obtained by injection molding (see Figure 2) and 2. doors with aluminum frames obtained by cutting and bending extruded bars (see Figure 3).

As shown in the above mentioned figures, both doors are composed, in fact, by two frames one inside the other: a fixed frame (i.e. the one fixed to the RV's wall) and an opening one.

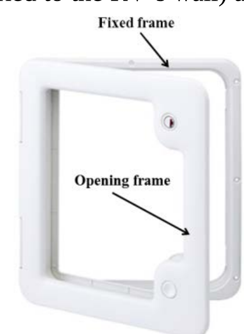


Fig. 2 Plastic door example [2]

Fig. 3 Aluminum door example [3]

Doors with plastic frame are generally characterized by a compact design and are often used for the cassette toilet, gas cylinders and water tanks. The panel of the moving part of the door is usually made of the same material of the RV's walls; sometimes, in case of small doors, the frame and the panel are even a unique plastic component, obtained directly from the injection molding process. Due to the complexity and high costs of this manufacturing process, these doors are usually produced in standard dimensions (e.g. 385 x 335 mm or 700 x 395 mm).

The production of different sizes (e.g. 400 x 600 mm), in fact, entails a huge investment for each new mold. On the other hand these doors (as shown in Figure 2) are often equipped with concealed hinges (integrated in the frame) that are aesthetically pleasing since there are no ledges protruding from RVs' walls. Moreover, the use of plastic materials entails lower cost compared with the one of alternative materials such as aluminum.

For the second type of doors, due to the manufacturing process (consisting of cutting and bending extruded aluminum bars), any door dimension can be obtained simply by adjusting the bars length. As a consequence, the frame size can be tailored to any wall opening. However, one of the main problems of this type of doors is the need of periodically tuning the cutting and bending machines in order to take into account possible environmental thermal variations leading to fluctuations in the geometry manufactured parts.

For this door typology, differently from what happens for plastic doors, in order to achieve 180° opening, the hinges stick out the wall as shown in Figure 3, thus resulting in an unpleasant aesthetic appearance.

In Table I, pros and cons of the two door types are summarized.

Tab. I Pros and cons of plastic and aluminum doors

Door type	Pros	Cons
Plastic frame	Low material cost and concealed hinges	Standard dimensions
Aluminum frame	Customizable dimensions	Cutting and bending machines tuning, visible hinges, high material cost

Moving from these considerations, this work is aimed to propose a Computer-aided design (CAD/CAE) of a different door type, capable to overcome the above mentioned drawbacks and to push forward the RV door technological state of the art. In particular, the idea is to develop a modular plastic door whose frames consist of extruded plastic bars, cut in required length, which are capable to comprise concealed hinges and are subsequently glued with plastic molded curves (see Figure 4).

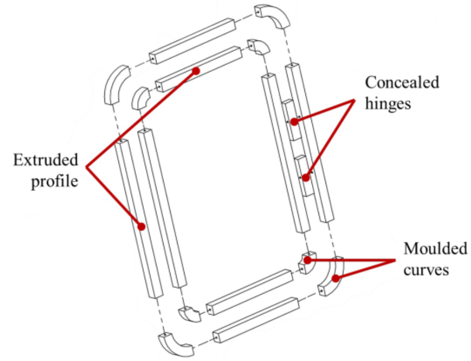


Fig. 4 Concept of the modular plastic door comprising concealed hinges

Such a solution allows the manufacturing of any desired dimension by overcoming the problem of the plastic frames (as already stated available only in standard sizes) and of the cutting and bending machine tuning. Moreover, the use of plastic material allows a significant cost reduction.

Obviously, the introduction of a new concept of the service door, based on novel modular plastic frames, entails the necessity of designing, validating and testing the proposed solutions, especially in terms of structural resistance. For this reason, the design of such new doors is carried out by means of the following tasks, as explained in the next sections:

1) Embodiment Design.
2) Slam test using CAE simulation.
3) Prototype manufacture and validation.

II. Embodiment Design

The above mentioned considerations, i.e. the use of plastic materials and of concealed hinges (capable of 180° opening), the capability of covering any possible dimension, together with the possibility of using door components (such as seals) already currently available on the market, have led to the design of the following components:

A. new modular fixed and opening frames
B. new concealed hinges
C. modular plastic door

A. New modular frames design

The first attempt to overcome the current technical state of the art in the manufacturing of service doors is the one provided by the work of Mihalec and Gregorcic [4]. In this patent a new module frame for window or doors, is described (see Figure 5). Such a frame is composed by sides, which are presented as bars (#1 in Figure 5) in selected length, and corners (#2). Each bar is made as multi-profile trim, and its profiles insure adequate sealing, insertion of the sealing rubber and setting of the frame on the wall.

The corners on both their ends summarize the profile shape of the profiled bar and they are made in a way that they can be easily connected to the profile bars with the help of adequate link elements (#3 and #4).

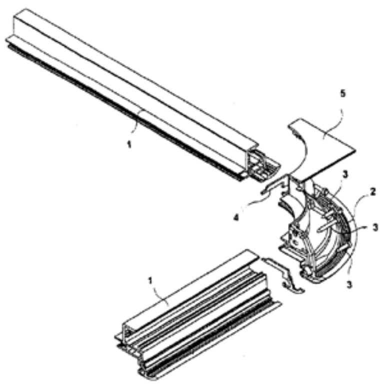


Fig. 5 Module frame from [4]

Analogously to Mihalec and Gregorcic's work, the proposed modular plastic door consists of frames made by extruded bars, cut in required length, and molded curves. However, in order to simplify and accelerate the assembly phases, the shapes of bars and curves are built so as to be easily fitted and glued with one another (see Figure 6).This is obtained by providing the bars with appositely designed slots which also serve as a housing for the hinges so that the hinges themselves result to be concealed.

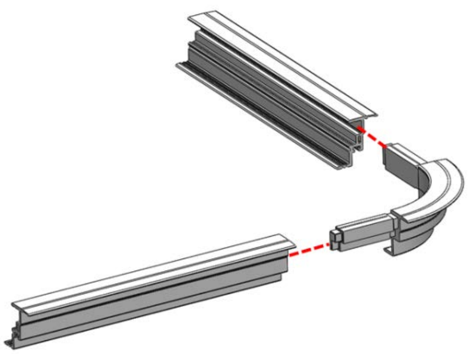


Fig. 6 Joint of curve and bars

Finally, the profiles of bars and curves allow the insertion of the sealing rubber and, in case of the fixed frame, the RV's wall mounting. In Figure 7 and Figure 8 the bars and the curves of the fixed and opening frames are shown.

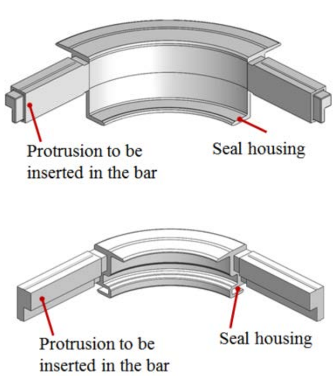


Fig. 7 Curve of the fixed (top) and of the opening (bottom) frame

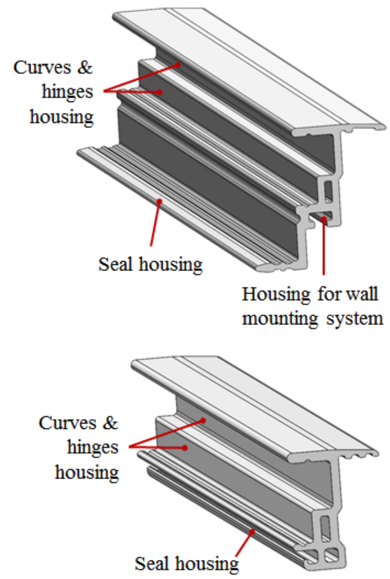


Fig. 8 Bar of the fixed (top) and of the opening (bottom) frame

Once curves and bars are assembled, water can possibly stagnate in some regions of the frame (see Figure 9) due to their particular shape. This represents one of the main drawbacks of this new system.

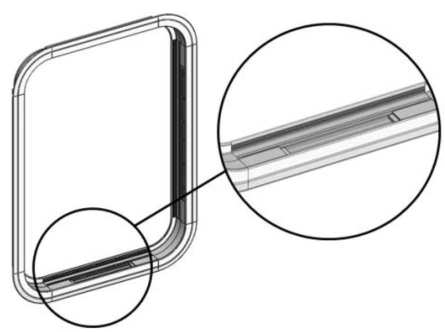


Fig. 9 Possible water accumulation regions in the frame

In order to overcome this issue, appositely devised rubber caps have been designed (see Figure 10).

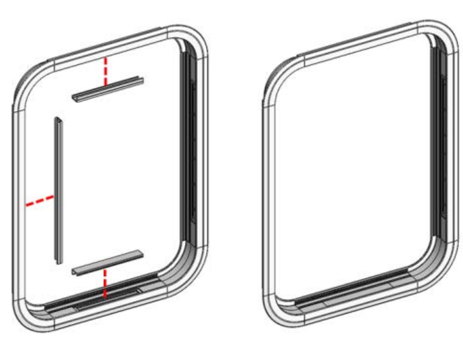


Fig. 10 Fixed frame and caps designed to protect the frame

B. New concealed hinges

Referring to concealed hinges, a distinction is necessary to be made between continuous (guided) hinges, in which the movements of the parts to be connected are coupled, and discontinuous (unguided) hinges, in which the pivoting motions of the parts to be connected are independent the one from the other [5]. In the discontinuous hinge, a collision of the parts during motion may result from the independent pivoting movements of the parts, which could lead to part damage, in particular on the edges of the parts to be connected [6].

For such a reason, in the last decades great effort has been made in order to develop different type of continuous hinges. Just to cite few, in [7] a hinge in which a guide is implemented by a spring is described; in [8] the guide system of the hinge is obtained using a linear guide, implementing an only approximately defined movement due to the necessary tolerances. One of the most relevant drawbacks of such hinge design is that the system usually is very weak, i.e. it features a low stiffness and insufficient strength especially for service doors which are particularly prone to impacts during closing phases.

A hinge capable to combine the advantages of continuous hinges and discontinuous hinges, i.e. to ensure dependent pivoting movements of the parts to be connected and/or a strict movement guidance as well as to guarantee the required stiffness and strength, is the one provided by [5].

Inspired by this concealed 180° hinge, developed for folding tables, a new hinge for service doors has been designed. In this hinge the guided motion is obtained thanks to the mutual position of the axes of two pivoting brackets that are offset by the same distance in two orthogonal directions (see Figure 11).

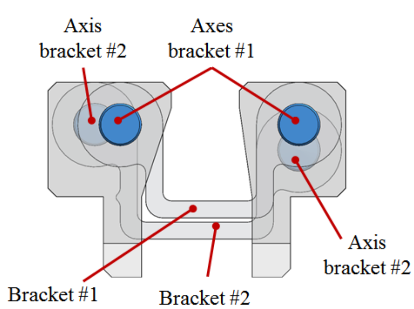


Fig. 11 Concept of the newly designed hinge

Moreover, in order to obtain an easy to be assembled hinge and to guarantee the required strength: 1) the two pivoting brackets are realized using cut extruded aluminum bars; 2) the two pivots are made of steel coated with low friction materials; 3) the housings of pivots and brackets are made of polyamide (PA) reinforced with 30% of glass fibers in order to be easily glued to the frame. In addition to glue, such housings may be screwed using fasteners to increase strength.

A detailed image of the developed hinge and a sequence of its guided motion are shown in Figure 12.

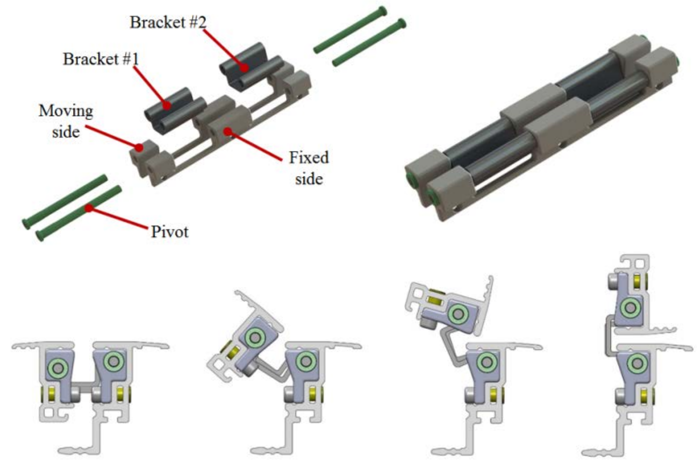


Fig. 12 Concealed hinge in exploded and assembled views (top) and motion sequence (bottom).

C. Modular plastic door

The assembly of the new modular plastic door is shown in Figure 13.

Fig. 13 Assembly of the new modular plastic door

In Figure 14 an exploded view of the new frames assembled with two hinges (#6), filler panel (#7), standard seals (#8, #9) and lock (#10) is shown.

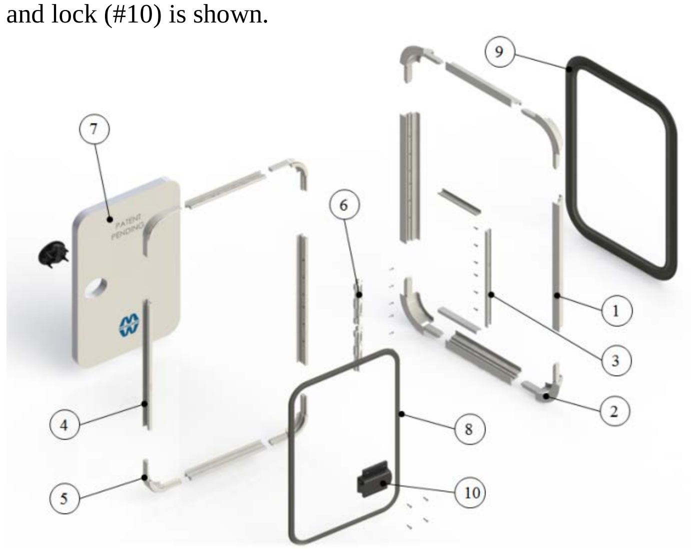


Fig. 14 Exploded view: #1 bar of the fixed frame; #2 curve of the fixed frame; #3 cap; : #4 bar of the opening frame; #5 curve of the opening frame; #6 hinge; #7 filler panel; #8 seal assembled with the opening frame; #9 seal assembled with the fixed frame; #10 lock

The filler panel (#7) is, commonly, a sandwich composed by an external layer made of fiberglass (1.8 mm thickness), an intermediate layer made of polystyrene (27.2 mm thickness) and an internal layer made of ABS (3 mm thickness). Since the bars (#1 and #4) composing the frames have, in the new design conceived in the present paper, to be manufactured using extrusion process, the best possible material to use for producing them is PVC. Curves (#2 and #5) are intended to be manufactured using injection molding; as a consequence the best option is to use PA reinforced with 30% of glass fibers.

III. Slam Test Using CAE Simulation

In order to optimize the design of the new door, a Computer Aided Engineering (CAE) analysis has been carried out using Altair® Hyperworks® suite. In particular, the optimization is carried out by simulating the slam of the service door under loads and speeds compatible with its common use in everyday life. In fact, as reported in literature [9-13] one of the best ways to evaluate the physical endurance of a door's construction (before manufacturing) is to perform slam tests using CAE.

Firstly, CAD data are pre-processed using Hypermesh®. Secondly, Radioss® Block 110 is adopted in order to solve the model using Finite Elements (FE). Finally, Hyperview® is used to perform post-processing. The reason for using Radioss® for solving the CAD model is that the slam simulation is an explicit highly non-linear problem under dynamic loadings as shown in Figure 15 [14-18].

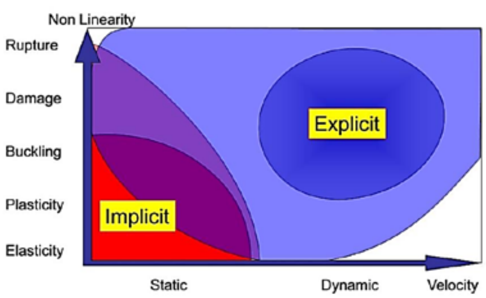


Fig. 15 Application fields of explicit and implicit analysis

With the aim of simulating the slam, some exemplificative assumptions are made to build the FE model:

- the sizes of the analyzed service door are 400 mm x 600 mm;
- the doors is equipped with two hinges (see Figure 14);
- the air inside the "o-section" rubber seal assembled with the fixed frame (see Figure 16) is neglected (precautionary hypothesis);
- the air resistance on door during closing phase is neglected (precautionary hypothesis especially in case of big sized doors);
- the resistance due to the air compressibility inside the cabin during closing phase is neglected (precautionary hypothesis);
- the friction in the hinges is neglected (precautionary hypothesis);
- the door lock presence is ignored;
- only the steel core of the pins is considered.

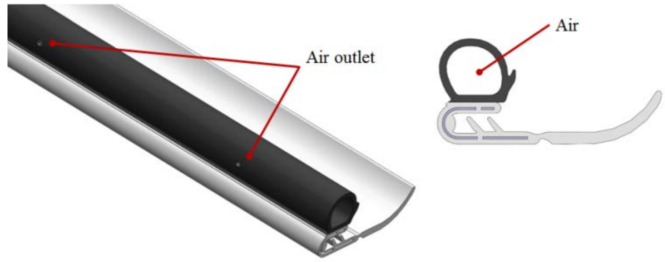


Fig. 16 Air and air outlet of the "O-section" rubber seal

A. *Geometry simplifications*

In order to facilitate the meshing phase and to reduce the processing time, the CAD models of door components have been modified as follows:

- Bar sections

  The bar sections have been modified by deleting all the fillets and by defining a constant thickness. In Figure 17 and Figure 18 the comparison between the designed sections and the simplified ones are shown, respectively, for the fixed and the opening frames.

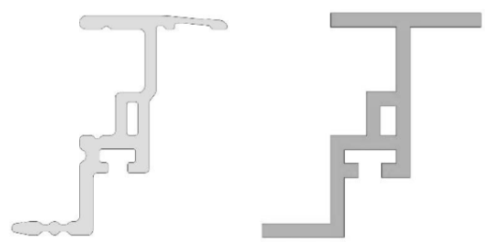


Fig. 17 Comparison between the original (designed) and the simplified bar section of the fixed frame

Fig. 18 Comparison between the original (designed) and the simplified bar section of the opening frame.

- Curves

  The geometries of the curves have been simplified by modelling them using a revolve feature applied to the simplified bar sections as shown in Figure 19. This means that the protrusions inserted in the bar (see Figure 7) are neglected so that the coupling between curves and bars is obtained by "gluing" only their touching faces.

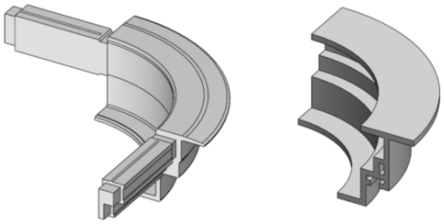


Fig. 19 Comparison between the original (designed) and the simplified curve of the fixed frame

- Hinges

  The geometries of the moving and fixed sides (see Figure 7) have been simplified by deleting all the fillets as shown in Figure 20.

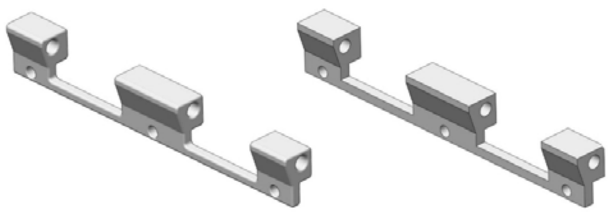


Fig. 20 Comparison between the original (designed) and the simplified moving side of the hinges

- Rubber seals

  Since the contribute of the air inside the rubber seal (see Figure 16) is ignored, the dissipation of energy due to the “o-section” shape can be neglected. As a consequence the rubber seal section has been simplified with a rectangular shape. The thickness of such a section has been considered equal to the one that the seal has when the o-section is completely compressed.

In Figure 21 a section view of the simplified model is shown.

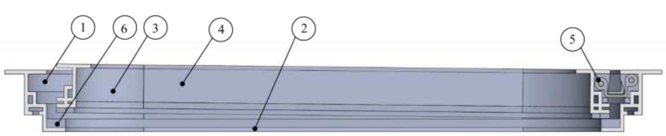


Fig. 21 Section view of the simplified model: #1 curve of the fixed frame; #2 bar of the fixed frame; #3 curve of the opening frame; #4 bar of the opening frame; #5 hinge; #6 rubber seal

B. *Mesh generation*

The simplified CAD model has been imported into Hypermesh® environment using the IGES format.

Frames have been meshed using *shell* elements [15] due to their high ratio between longitudinal dimensions and thickness. Accordingly the frame mid-surfaces have been extracted so that the mesh construction is straightforwardly allowed (see Figure 22).

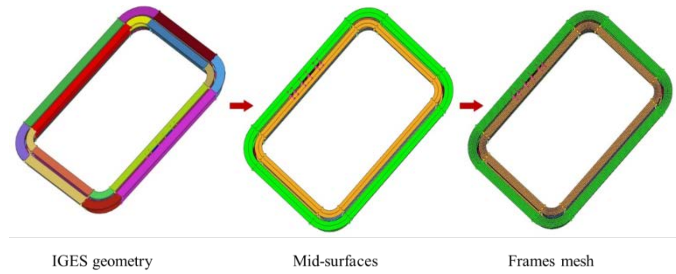


Fig. 22 Frames mesh generation

A mapped mesh of solid *brick* elements [15] has been used for the rubber seal while solid tetrahedral elements have been used to mesh all hinges components with the exception of the four pivots (modelled using rigid region, as shown in Figure 23).

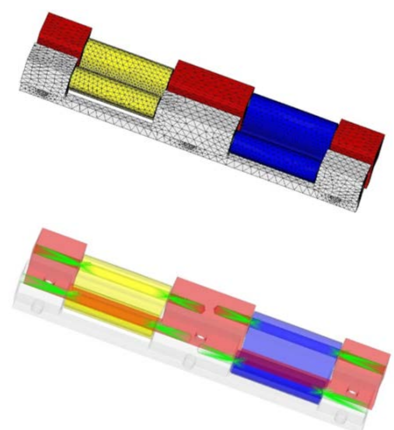


Fig. 23 solid mesh of the hinge showing the rigid regions used to model the pivots

Moreover, being the filler panel a sandwich structure, it is meshed using shell elements for inner and outer layers and *brick* elements for the core.

The connections hinges-frames and filler panel-moving frame (physically obtained using glue) are modelled by merging the coincident nodes thus implying that parts do not detach during the slam test.

Finally, *contact pairs* have been inserted between all the surfaces possibly in contact during the slam phase.

In Figure 24 the final FE model is depicted.

Fig. 24 FE model

C. Materials

In Table II the materials used for the FEM are listed. With the exception of rubber seal, all the materials are considered to be isotropic linear-elastic. Rubber seal is modeled according to Ogden law [19-21] using the parameters stated in Table III.

Tab. II Materials

Material	Density (ρ) [kg/m^3]	Young module (E) [MPa]	Poisson module (υ)	UTS [MPa]	Fatigue UTS [MPa]
Rigid PVC	1300	2410	0.38	40	15-20 MPa (1 Hz)
PA 30% glass fiber	1370	7200	0.34	130	
Al2011	2800	69000	0.3	220	100
ABS	1000	2000	0.38		
Fiberglass	2100	20000	0.35		
Rubber (EPDM)	1000	/	0.35	/	/
Polystyrene	35	100	0.38		

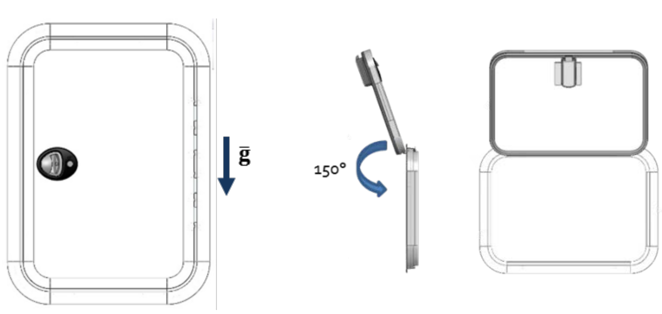
Tab. III Ogden model: constants used to model rubber (EPDM)

μ_1	μ_2	μ_3
6.3e-4 MPa	1.2e-6 MPa	1e-5 MPa
α_1	α_2	α_3
1.3	5	5

D. Loads and boundary conditions

The slam test is performed by using the configuration in Figure 25a where the moving frame is loaded by gravity force and by inertial forces which arise when the moving frame impacts on the fixed one. Since an a priori estimate of the initial door speed (applied, for instance, by a person pushing the door) is not trivial, such a velocity has been assumed to be the one characterizing the configuration of Figure 25b. In this configuration, the moving frame initially describes a 150° angle with the fixed one.

The value of the door angular velocity can thus be analytically evaluated by using the compound pendulum equation [22] considering that the only acceleration acting on it is the gravity. In particular, the impact speed has been estimated at the instant in which the moving frame describes a 3.5° angle with the fixed one and results approximately equal to 10 rad/s.



(a) (b)

Fig. 24 a) configuration used for slam analysis and b) configuration used to estimate the impact speed

In order to simulate the assembly (by gluing) of the fixed frame with the RV's wall, the degrees of freedom (DOFs) of all nodes belonging to the surfaces glued with the wall have been constrained (see thick line in Figure 25).

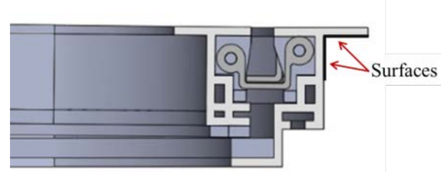


Fig. 25 Surfaces glued to the RV's wall

E. Results

Figure 26 shows the distribution of von Mises stresses induced within the service door in the most critical step of the slam test. According to FE results, a maximum stress of 120 MPa is reached in the lower bracket.

Fig. 26 Von Mises stresses induced in the most critical step of the slam test

In fact, almost all the bracket elements are subjected to a stress higher than 50 MPa, as shown in Figure 27 (isostress [23] diagram at 50 MPa).

These are undesired conditions since, even if the system has been modeled under precautionary hypothesis, the maximum desired value to be reached during the slam test has to be lower than 40 MPa.

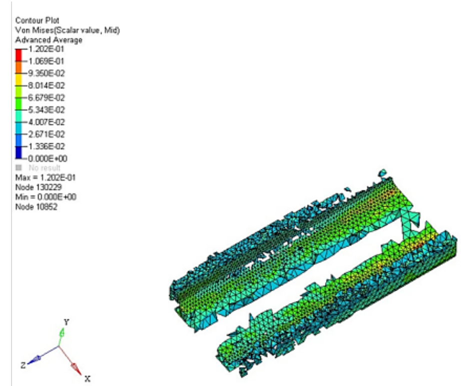


Fig. 27 Isostress diagram showing that most of the elements of the bracket are subjected to a stress higher than 50 MPa

Accordingly, in order to reduce the stress acting on both the upper and lower brackets during the slam test, their design has been slightly modified by increasing their overall thickness and by changing their fillet radii (see Figure 28).

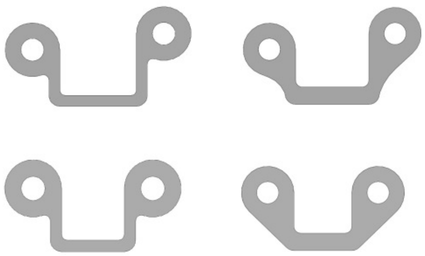


Fig. 28 Left: original sections of the upper and lower brackets (respectively); right: modified sections

After the model has been changed according to the design modifications on the brackets, a new FE simulation has been performed using the same configuration described in section D. The sequence of the performed slam analysis is depicted in Figure 29.

Fig. 29 Slam sequence

Results, depicted in Figure 30, show that the maximum stresses induced to hinges (in brackets) is lower than 40 MPa, as required, with most of the elements subjected to a stress lower than 25MPa.

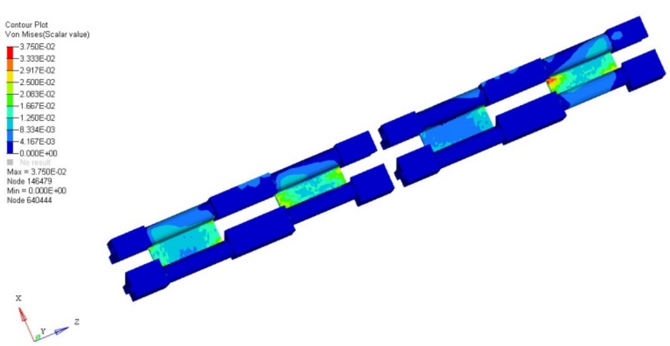


Fig. 30 Von Mises stress on hinges after the re-design process

Furthermore, it has to be noticed that the induced stresses on the frames and filler panel are not critical since, as shown in Figure 31, the maximum stress value is lower than 15MPa and located in a limited area of the assembly.

Since rigid PVC ensures a Fatigue UTS in the range 15-20 MPa, simulation shows that the system, once the brackets are modified, is able to endure multiple slams.

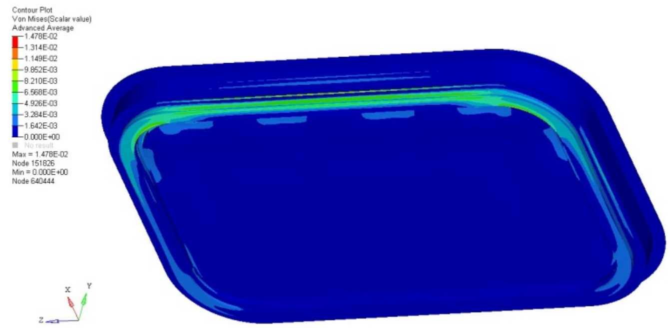


Fig. 31 – Von Mises stresses on the frames and filler panel.

IV. Prototype Manufacture and Validation

In order to verify the correctness of the designed door (in terms of general dimensions of the components, assembling and kinematics) and to test the effectiveness of the slam test, a physical functional prototype model has been built using Rapid Prototyping (RP) techniques. Since the door components have been assumed to be mostly in plastic material (with the exception of the hinge brackets that will be aluminum made), among the RP technologies available in the market, the Fused Deposition Modelling (FDM) has been selected. FDM technology uses a thermoplastic filament, which is heated to its melting point and then extruded, layer by layer, to create the object. Materials used in this process are, for instance, polycarbonate (PC), acrylonitrile butadiene styrene (ABS), polyphenylsulfone (PPSF) and PC-ABS blends [24].

The door prototype has been realized using Fortus 400 machine (produced by Stratasys Ltd.) with a resolution on the z axis equal to 0.125 mm. Among the thermoplastic materials usable for this machine, ULTEM® and ABS-M30 have been chosen. In particular, due to its excellent tensile and bending strengths [10], ULTEM® has been used for hinge's pivots and brackets, while the other components have been made using ABS. Since FDM machines generally realize shafts with diameters 0.1 mm greater and holes with diameters 0.1 mm lower than the nominal ones, some minor changes have been made to door parts in order to make the assembly possible.

The manufactured parts of a 600 x 400 mm service door are shown in Figure 32.

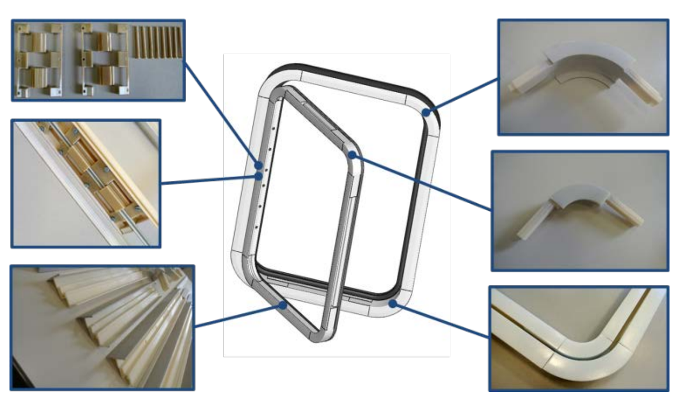


Fig. 32 Door components obtained by using RP techniques

In order to improve the surface finishing and appearance, the components of the two frames have been plastered, sanded and painted.

A preliminary evaluation performed on the prototype has highlighted some minor issues in terms of kinematics and aesthetics. Firstly, an unexpected vertical displacement of the opening frame (see Figure 33a) has been detected; secondly, an unforeseen rotation around the axes shown in Figure 33b has been observed. Such movements can be attributed to excessive clearance between the pivots and their holes, thus an accurate tolerance analysis is advisable before building the hinge molds.

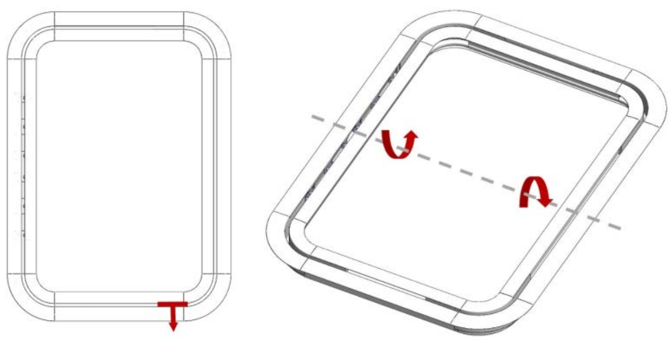


Fig. 33 Unexpected vertical displacement (a) and unforeseen rotation (b) of the opening frame.

Finally the prototype highlighted an aesthetic problem which had not been detected from the CAD model. The problem is related to the rubber seal (usually black) between the fixed and the opening frame which is, in fact, visible in the gap between the two frames as shown in Figure 34.

Fig. 34 Seal visible in the gap between the frames

In order to overcome this issue some changes have been made on the section of the opening frame as highlighted in Figure 35.

Fig. 35 Prototype section (on the left) of the opening frame and modified one (on the right).

V. Conclusions and Future Works

An innovative service plastic door has been developed and prototyped using Rapid Prototyping techniques. The frames making up the door have been designed as extruded plastic bars, cut in required length, which are glued with plastic molded curves.

The shape of the frame sections has been developed in order to house concealed 180° hinges. The modular proposed solution allows: firstly, the manufacturing of any desired door size by overcoming problems characterizing commercially available devices; secondly, a more pleasant aspect due to the use of concealed 180° hinges; thirdly, a cost reduction due to the use of plastic material.

In order to evaluate the physical endurance of the door under working conditions, CAE slam test has been performed. This allowed to partially re-design the brackets in order to guarantee a fatigue UTS of the system lower than the desirable maximum value (40 MPa).

In order to tackle with the problem of possible undesirable door movements (such as the ones detected in prototyped device) future work will be addressed to perform an accurate tolerance analysis on the hinges will be performed using STA approaches and tools.

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