REPARABILITY AND RESIDUAL MECHANICAL BEHAVIOUR OF PULTRUDED PROFILES

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SUMMARY: Today, service monitoring for maintenance is a major aspect concerning durability of composite structures in industrial applications. According to these considerations, repair concepts should be a part of specifications in the product quality assurance schedule. These repairs, sometimes costly, are defined by the following stages : damage detection (for example, by NDI methods) and preparation of damaged areas. The present study deals with manual and cheap repairing on glass/polyester damaged pultruded structures. These repairs require an appropriate machining of the damaged area and a specific patch application.
First, fatigue tests provide an optimisation of repair patch per profile type submitted to standard drilling. Secondly, impact tests are used to simulate pragmatic damages in original shapes. Next, an analyse is carried on the reparability of the structures according to the damage extent introduced by the different impact configurations. With the higher limit of feasible restoring, repair procedures made after impact solicitation are validated by satisfactory residual behaviour in static, fatigue and impact tests.

KEYWORDS: repair, patching, pultruded structures, residual properties, damage, impact tests, flexural tests.

INTRODUCTION

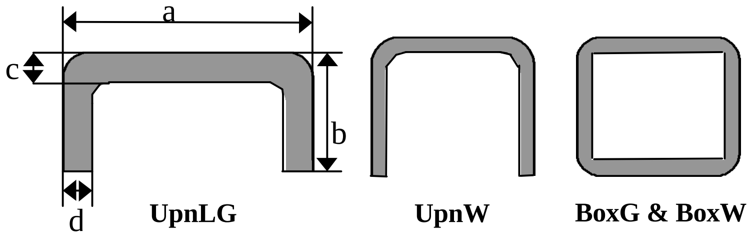
Pultrusion is one of the fastest and most cost-effective process by which composite can be manufactured. Recently the application of pultruded fiber-reinforced plastic (FRP) composites in industry has increased. These composite structures have desirable properties in corrosive and chemical environment. For all these reasons, pultruded composite structures are being more and more competitive with steel and concrete for different constructions (roadside safety structures, structural applications in aggressive environment (chemical), etc.). In these applications, impacts of stone and shocks of maintenance device can damage pultruded shapes and modify their durability. Then, appropriate repair procedures become essential but must be simple, cheap and feasible in situ, overall, in accordance with the low cost of the pultruded materials.

The present study deals with performances of manual repairing on glass/polyester damaged pultruded structures. Both initial and residual mechanical behaviour of the virgin and repaired structures are compared and studied. The aim of this work is to determine the domain of reparability of each pultruded shape studied associated with its solicitation. Two limits are defining this domain. The lower one is the minimal damage size (standard or impact damage) centred on high level constrained parts and which affects the residual mechanical behaviour of the shape. Above the higher limit, damages are so severe that no repair can restore as much as possible of the original material properties.

EXPERIMENTAL

Materials

Four standard profiles called BoxW, BoxG, UpnW and UpnLG are studied in this work. Two geometrical types have been investigated, boxbeam for BoxG and BoxW and "U" sections for UpnW and UpnLG. These beam profiles are composed of the web (the upper and the lower skins) and the flanges. Three types of matrix (resins+filler) were also investigated (W for white, G for grey and LG for light grey). Two different types of Pultruded stacking sequence were considered. These sequences were constituted with a continuous strand Mat (M) and Unidirectional Roving fibers (R). The thickness of these sequences was 5 mm for the M/R/M sequence (BoxW, BoxG and UpnW) and 8 mm for the M/R/M/R/M sequence (UpnLG). Profiles geometry and different reinforcements in cross sections are shown in Fig. 1.



Profile and Sequence	**Profile geometry a*b*c*d (in mm)**
UpnLG M/R/M/R/M	90*35*8*8
UpnW M/R/M	50*55*5*5
BoxG & BoxW M/R/M	50*50*5*5

Fig. 1 : Materials cross sections and pultrusion sequence configurations

Three matrix sets were considered is this study. These sets are some mixture of the same polyester unsaturated isophtalic resin and three different kinds of filler group and additives (fillers, pigment and other retardant or absorbers). These additives are joined in order to prevent environmental degradation such as UV's aggression, etc. Due to confidential reasons, these three matrix mix are identified by their colour ; W for white matrix, G for Grey matrix and LG for the Light Grey one. The separation of the fillers from the matrix was performed to evaluate the type and the proportions of filler in the matrix : the volume fractions in fibre are about 46% for all profiles studied.

Repair techniques

Four repair procedures are investigated :

1- a glass/polyester potting compound
2- a polyester reinforced glass fibers film which hardens trough UV curing
3- a by-hand manufactured glass/resin patch with stratification of Mat and woven fibers
4- a pre-polymerised by-hand manufactured glass/polyester patch with stratification of Mat and woven fibers which is stuck to the structure by an epoxy adhesive

In fact, the results concerning the two first repair methods are not shown in this paper. They are not effective for structural damages and are only advised for aspect defaults.
Globally, these repairs, inspired from simplified aeronautical repair techniques [1, 2] and restoring works on polyester structures [3], require an appropriate machining of the damaged area. Also, a specific patch application is necessary for good adhesion with the neighbouring undamaged parts of the profile. Concerning the manufacturer specifications, repair shouldn't modify the external aspect of the product. In result, the repair patch must be flush with the external profile surface and the procedure must be simple, cheap and feasible in situ. About repair techniques, following steps should be respected :

- a- A global envelope defines the damage zone. This one determines the repair extent and the healthy zone necessary to make the patch to adhere (Fig. 2 & Fig. 4).
- b- The machining is realised by a buff wheel provided with an oblong carbide drill. Damage envelope is eliminated and a cone-shape curving is made (Fig. 2 & Fig. 4).
- c- For repairing, a stacking of several mats and woven fibers of glass E is realised by starting with plies of mat 100 g/m² (guaranty of a good formability and adhesion with the back of the cone, see Fig. 4). However, for confidential reasons, the different mats and weaves patch proportion is not described in this paper.
- d- The moulding process used is a simple hand lay up at room temperature. The repaired specimen is put under press so the patch is a little compacted and the resin flows well through the plies of the patch.
- e- After polymerisation, the patch is sanded down to be flush with the surface skin and a gel coat could be applied for the painting and the external aspect.

Moreover, especially about the fourth method, a removing film is applied at the bottom of the cone-shaped machining, so during the polymerisation the patch well matches the shape, next it is taken off with the film and finally stuck by an epoxy adhesive.

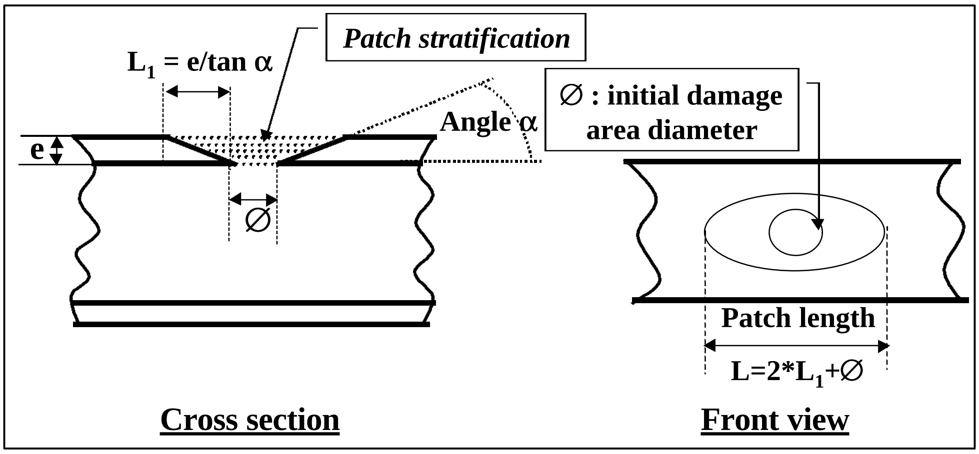


Fig. 2 : Repair techniques applied to the pultruded structures (About cross section and front view, see Fig. 3)

Testing

A comparative experimental investigation and some numerical verification are carried out to determine and analyse the performances of the different repaired shapes. Both initial and residual mechanical behaviour of the virgin and repaired structures is studied with four-point bending tests in static and fatigue and under low-velocity impact loading. The four-point bending test configuration has been chosen in order to have both a pure bending moment in the central part of the profile and a pure shear solicitation at the extremities. The total span of the shapes (L) is 900 mm. The static tests were conducted at a cross head speed of 2 mm/min. The fatigue ones were also performed at the frequency of 3 Hz and an R ratio equal to 0.1

(R=Fmin/Fmax). A failure criterion was chosen to be at 5 mm over the maximum central deflection obtained from static tests. These fatigue tests were not possible for UpnLG because of too important deflection for the machine hydraulic system. Moreover, Acoustic Emission and observations (cutting out and microscopic observations) are used to describe more precisely damage mechanisms and damage area for the different states in residual static, fatigue and impact behaviours. Here, two steps are investigated in order to analyse the reparability of the structures.

Firstly, as shown in Fig. 3, optimisation of repairs are obtained by two configurations of standard drilling in BoxW, BoxG and UpnW, with the context of fatigue tests more severe than static ones :

> (1) : The upper part of the web is drilled with a diameter of 25 mm at the center of the pure flexural zone for BoxW, BoxG and UpnW (see Fig. 3).
> (2) : One flange of each symmetric sheared extremities is also drilled at the center with a diameter of 25 mm. This case is only carried out for BoxG (see Fig. 3).

Secondly, optimised repair methods are analysed and validated in configuration (1) on all profile types (see Fig. 3) by iso-velocity and iso-energy drop weight impact tests conducted at different damage levels (velocity : 4 to 6 m/s and energy : 50, 80 and 110 J). These impact tests are made with a drop weight tower and first performed on virgin beam specimen in the configuration 1 (Fig. 3) for residual four point bending tests. Moreover, they are carried out on clamped specimen with the same span of 900 mm than flexural tests configuration. The impactor is a semi sphere with three nose radius : 12.5 mm (small-impactor : SI), 25 mm (medium-impactor : MI) and 50 mm (big-impactor : BI) which provides different types of damages. This dynamic solicitation generate complex failure modes in the material and an analyse is carried on the reparability of the structure according to the damage extent introduced by the different impact configurations and the residual strength observed. With the higher limit of this domain of reparability, residual flexural tests in static and fatigue criticise and validate the repair procedure made after impact solicitation. Also residual drop weight tests are performed upon an artificial repair area equivalent to a repairing made after an impact at 80 J. This investigation shows the different impact behaviour and sensitivity of the structure after repairing. Next, flexural residual tests (static and fatigue post-impact post-repair tests) verify the change of the initial structural behaviour.

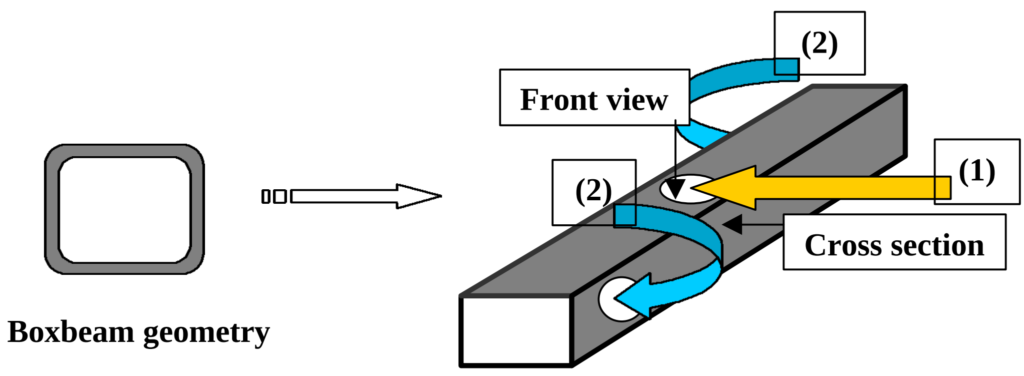


Fig. 3: Example of pultruded shape and damages and repairs sites configurations

RESULTS AND DISCUSSION

Virgin mechanical behaviour of the structures

Undamaged pultruded profiles are first evaluated in static and fatigue to measure their referential behaviours. Concerning static tests, rigidity (ratio F/δ when δ is the central displacement of the shape), failure modes and strength (Fmax) are shown in Table 1. Moreover, Acoustic Emission cumul provides the damage threshold (F*) of each structure.

Table 1 : Static properties and failures modes of undamaged beams

Profile type	Rigidity : F/δ (N/mm)	Strength : Fmax (N)	Damage threshold : F*/Fmax	Failure modes
UpnLG	323 (2%)	17050 (6%)	0.51 (11%)	Failure in flanges due to shear and bending combined stresses
UpnW	595 (3%)	2236 (4%)	0.65 (9%)	Compression mode just below the load bearing system and Shear failure at the top corners in the beam central part
BoxW	850 (5%)	23650 (5%)	0.57 (8%)	As UpnW
BoxG	850 (5%)	22900 (6%)	0.57 (8%)	As UpnW

Concerning fatigue behaviour, S-N curves have been determined for BoxW, BoxG, and UpnW. The two boxbeam shapes have similar behaviour and endurance limit Fmax at 47.5% of their maximal load reached in static. This value is at 52.5% for UpnW. For cost reason and samples number, only one level of stress per profile is next retained to investigate damaged and repaired shapes in residual fatigue tests. This one is just above the endurance stress, that means Fmax at 48% of the static maximum load for the Boxbeam profiles and 53% for UpnW. At this load levels, “U” shape reaches about 350 000 cycles and the boxbeam ones roughly 650 000 cycles.

Repairs optimisation

To optimise repair procedure, several parameters are investigated. Drilling configuration (1) is used first to test, the angle of the cone-shaped curving (3° to 10° are investigated), secondly, the resin employed during the hand lay up process (polyester, vinylester or epoxy resin), thirdly, the fiber orientation of the patch, fourthly, the repair methods. Finally, the site of the repair depending on the mechanical zone of the shape is also studied with the third repair method. Fatigue solicitation is a very severe mechanical situation and occurs an accurate repair patches selection. For all patches studied and situated in the compression upper part of the pure flexural zone, a delamination failure is first observed in the center of the patch. Next a buckling under compression stress is induced in the repairing and the delamination failure grows at the interface patch/original structure from the center to the extremities of the patch. Finally, the profile fails by shear propagation coming from the patch crack to the upper corners of the shape.
Concerning the angle of the cone-shaped curving, a difficult compromise should be respected. First, a minimal extent of the machining is necessary for the patch to adhere and withstand in durability. Secondly, a so great machining area induces a structural weakening and actually, repair procedure becomes too long in time. An angle of 3° respects this compromise. About resin employed for the stratification (third repair method), epoxy one is more effective than the others (isophtalic polyester, orthophtalic polyester or vinylester) and provides the better interface between the patch and the parent material.

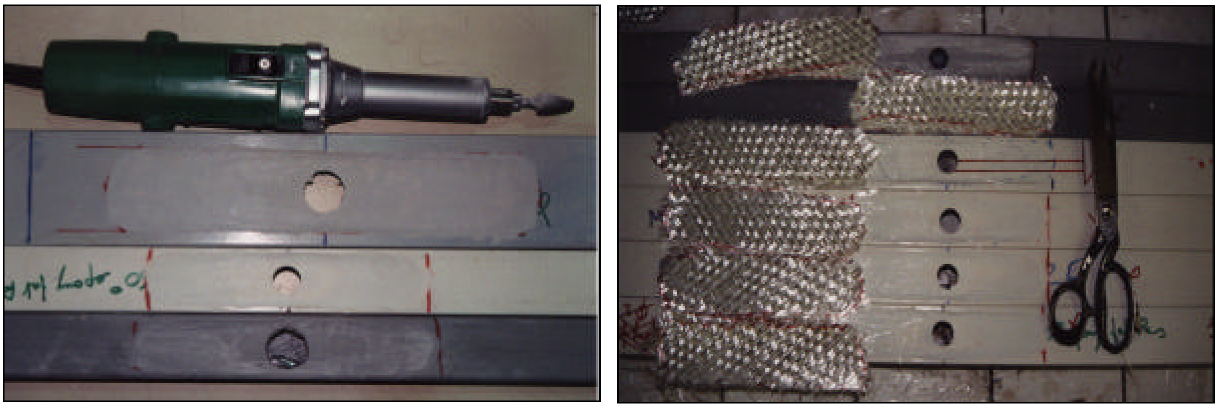


Fig. 4 : Two steps of the repair on drilled shapes : machining and preparation of weaves

The comparative study about different fiber orientation in the patch is obviously carried out with epoxy resin and 3° angle of machining. The orientations in relation to the profile length are obtained with [0/90°] taffeta or unidirectional weaves sown on a chopped strand mat. The same placing about the effectiveness of the different patch orientations is observed with the BoxW, BoxG and UpnW. [±45°] and above all [±60°] orientations manage better the problem of delamination. In fact, patches introduce a singularity in the parent material; so, a relative displacement and shear stress at the interface are due to the transfer of load between the parent material and the restoring zone. However, a relatively close rigidity between the repair patch and the profile shouldn't be applied because of higher stress introduced in the interface. Also, UD orientation confirms this phenomena with an early and rapid delamination without buckling in the patch. On the other part, [±45°] and [±60°] orientations with lower longitudinal stiffness, absorb higher damage energy inside the patch during fatigue cycles. They are more suitable for interface shear solicitation and relax better the stress delamination. About BoxG structure, [±60°] stratification made with UD weaves presents the best durability. But for practical reason, this repair configuration is not advised. In particular, unidirectional woven fibers are difficult to cut and rightly be orientated in the cone-shaped curving of the machining.

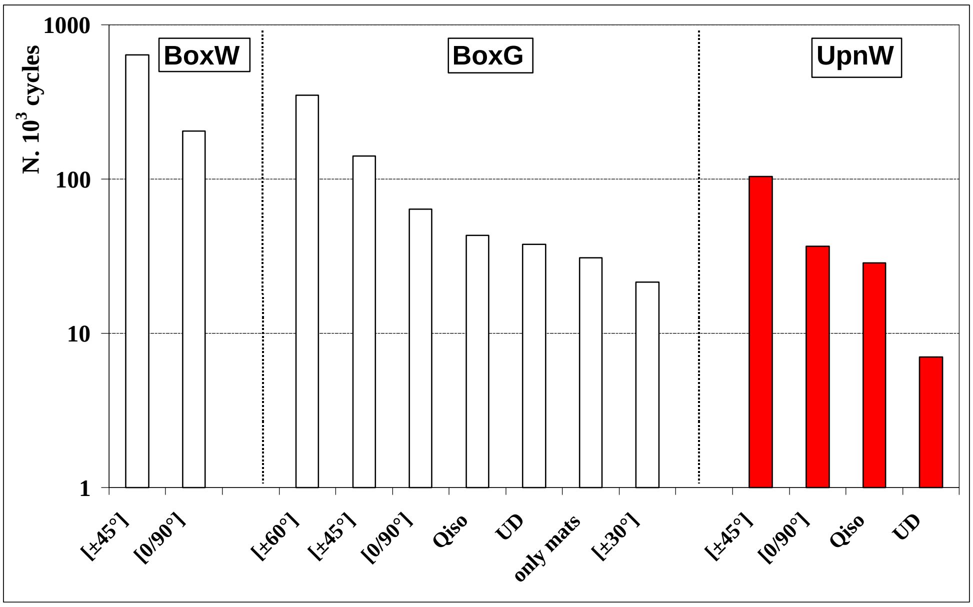


Fig. 5 : Residual fatigue results : Optimisation of patch orientation by topside repairing

In addition, comparison between behaviour of open (UPN beams) and closed (boxbeam profiles) repaired shapes can be shown. BoxW seems to be more tolerant to the damage than BoxG and so, easier to repair. This could be explained by the difference in matrix composition between the white and the grey matrix (influence of resin additives on the failure behaviour, [4]). Besides, open shape UpnW offers the possibility to repair also by the rear face and however with respecting the specifications (no change of the external aspect of the product). So, internal reinforcement can be added to this one initially manufactured on the topside and then, improves the durability of the repaired open profile. <u>Comparative fatigue tests show than internal patch with [0/90°] orientation associated with [±45°] repair patch on the visible face of the upper skin is then the most effective couple (452 000 cycles reached)</u>. In fact, inner side of the shape is not concerned by the interface shear solicitation as the top face, but by a tensile stress and above all opening of profile corners. In result, [0/90] weaves recover the rear face of the upper skin shape and the half height of the inside flanges. In regard of width and thickness of the open profile UpnLG, inside patch seems to be useless. However, a very critical damage in this structure type could induce to adopt a similar solution used for UpnW.

Concerning the fourth repair method, disappointing results are observed. A rapid delamination occurs in the epoxy adhesive joins. In fact, this repair method provides a less close interface than the in-place stratification method and so a bad transfer of load. Also, fatigue solicitation introduces a thermal stress in the interface, which reduces badly the adhesive properties. So the pre polymerised and stuck patch is not selected for the validation phase of repair procedures.

Finally, damage site influence is investigated by two symmetric drilling in the extremities in shear of the boxbeam shape BoxG. A good and comparative durability is observed between this repair site and a repaired flexural zone. [±45°]-patch orientation is the accurate repair configuration due to the shear solicitation in flanges.

Optimised patch per profile type is summarised in Fig. 6.

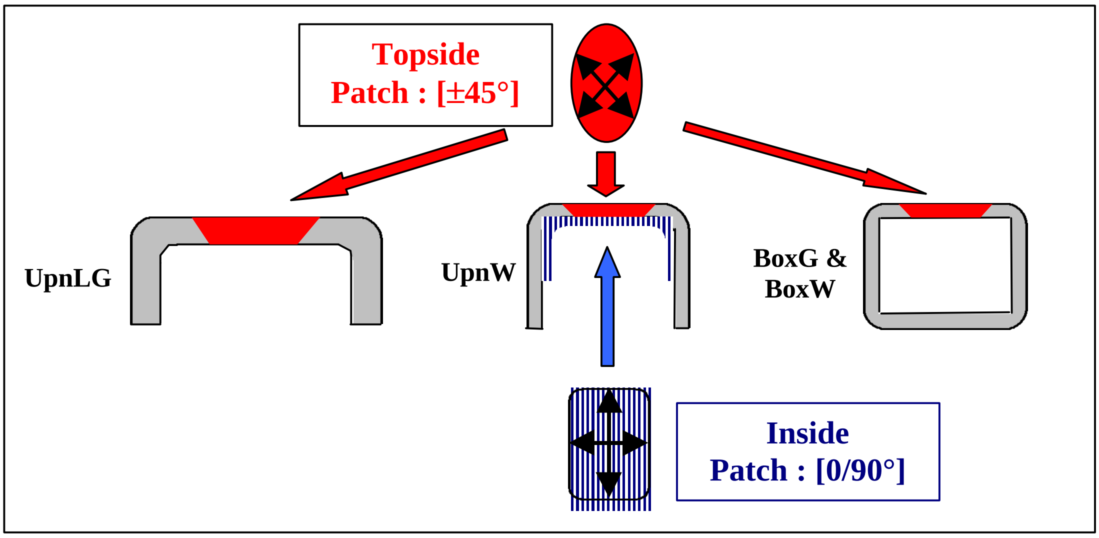


Fig. 6 : Optimised patch orientations per profile type

Post impact residual strength of pultruded shapes and analyse of the reparability

Standard drillings have been good and easy way to optimise repair parameters but they don't represent real damages in structure life. Impact solicitation simulates better shocks of stone and maintenance device. A precedent study [4] has analysed the damage modes by drop weight loading on other similar pultruded shapes. The influence of test parameters such as impact velocity, impactor mass and size was emphasised. Some verification tests made on profiles studied confirm the complex impact damages already observed [4] : shear and bending cracks, interfacial delamination inside the upper skin of the web. Post impact residual static and fatigue tests provide an energy threshold of 80 J for all shapes [5]. Moreover, the worst configuration for residual evaluation is the Big Impactor (BI) diameter (50 mm) coupled with the lowest impact velocity (4 m/s)[5]. When this energy level is reached or overshot, longitudinal cracks in the upper corners of boxbeam shapes and UpnW (except for UpnLG) were also noticed and induce a priori a difficult zone to repair (keystone role of the corners).

According to impact and post-impact results, the BI & 4m/s and 80 J or 110 J configurations (high reparability limit estimated) are chosen to evaluate the effectiveness of optimised repair procedures.

Optimised repairs validation and impact behaviour of repaired beams

Residual static and fatigue results about post-impact repair

Similar elastic behaviour and failure modes compared to virgin profiles are observed. Equivalent residual strength is recovered and above all concerning repair post-impact at 110 J for UpnLG. In fact, impact loading at 80 J doesn't modify strongly original static behaviour and post-impact repairs preserve this situation (see Fig. 7).

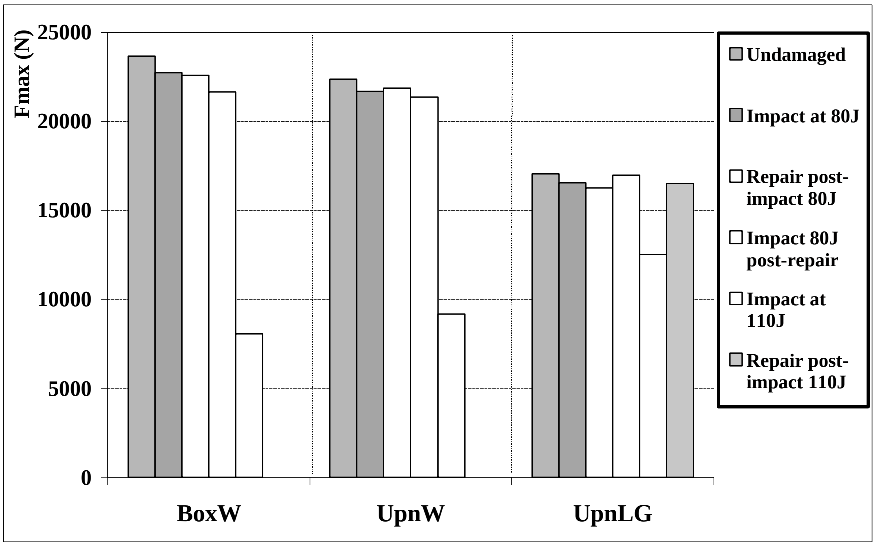


Fig. 7 : Residual static strength of different undamaged, impacted, and repaired shapes

However, real difference in results is shown by fatigue tests (see Fig. 8). Repairs post-impact at 80 J and 110 J don't restore initial lifetime of pultruded shapes (350000 cycles for UpnW and 650000 for BoxG and BoxW). In fact, impact loading has introduced so detrimental failure modes in structures.

However, contrary to damaged profiles, repaired ones give an interesting security margin. Also, on the one hand, restored structures should be particularly monitored in maintenance operations. On the other hand, initial structural calculation can take into account a future possible repairing, so an accurate security coefficient can be applied to assure an acceptable residual lifetime strength for repaired shapes.

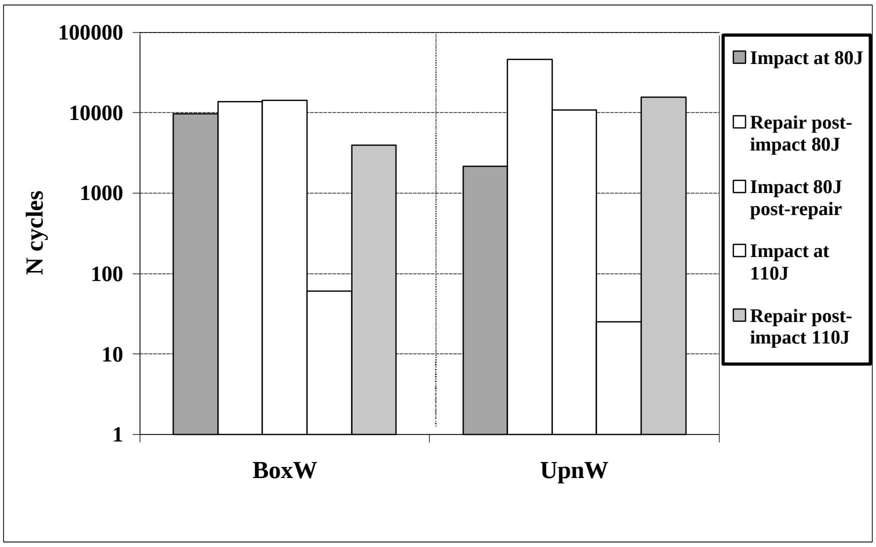


Fig. 8 : Residual fatigue results of different undamaged, impacted, and repaired shapes

Impact and post-impact behaviour of repaired shapes

In the same context of security assurance, the behaviour of impacted and post-impact repaired profiles is analysed. By the way, new drop weight test at 80 J are performed upon an artificial repair area equivalent to a repairing made after an impact at 80 J. Also, impact force (F= m.γ) versus time curves (Fig. 9) for repaired specimen show contact time duration shorter and maximum load higher than original beams.

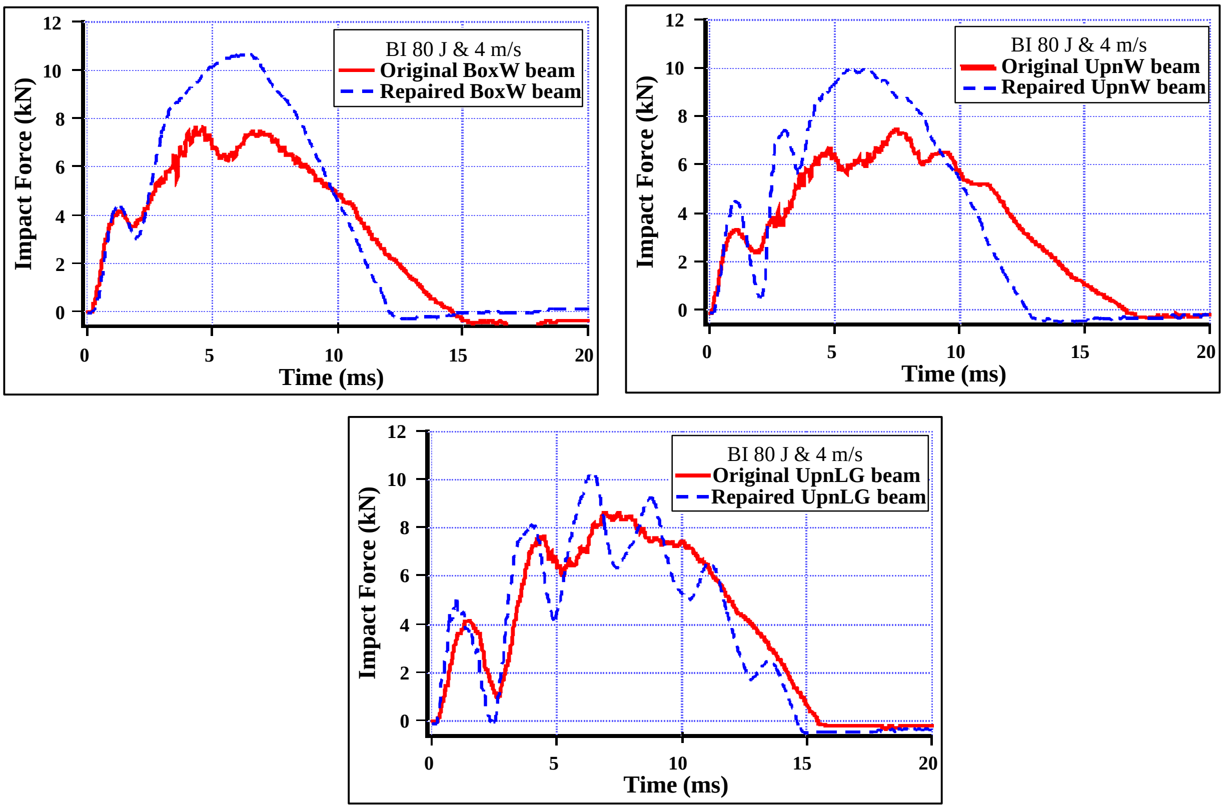


Fig. 9 : Impact force versus time curves of original and repaired beams

In fact, patches have superior dynamic rigidity than parent material. They actually create a new local structure, especially for UpnW with its inner [0/90°]-patch reinforcement that

embrace upper corners. Moreover, influence of the impactor nose is emphasised : its diameter is in the same ordering size (50 mm) than the UpnW and Boxbeam shapes width. In these cases, repaired area influences more the global response of the structure under impact loading. These reasons explain the superior difference of behaviour between virgin and repaired shapes concerning UpnW and BoxW in front of UpnLG (90-mm width and repair only at the topside, see Fig. 9). Also impact force versus time curves form (less disruptive for repaired beams) and post-impact observations show less critical damage extent concerning repaired shapes. In the same way, the patch consumes a higher elastic energy and the repair area seems to confine the impact damage and then safeguard a little the rest of the structural integrity.
Furthermore, impact post-repair residual static and fatigue tests (impact 80 J post-repair, see Fig.7 & 8) provide more safety results than original shapes impacted at the same energy level.

CONCLUSION

To conclude, this study shows the benefit of repair pultruded profiles by simple and cheap manual procedures. However, the most difficult is first define exactly the damaged zone and so the reparability of the shapes. Then, structure life can be extended next accidental deterioration even if maintenance monitoring should be more scrupulous after restoring. Concerning very severe damages, these repair methods could be temporary solution in waiting for the product change. In this context, repaired pultruded profiles have a satisfactory behaviour in residual static, fatigue and impact solicitations.
To complete this work, a current study defines more precisely failure modes of virgin and repaired structures (localisation and chronology of the damage mechanisms). For instance, accurate strain gauges instrumentation is bonded on profiles during static and impact tests. Also, an overview of the influence of physical properties and morphology of the repairs (filler mass fraction, voids concentration, geometry and adhesion) is given. Finally, the interaction between two types of design and process very different is underlined : repair patches and pultruded shapes.

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