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Adhesive Bonding Technology in the Automotive Industry

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INTRODUCTION

A constantly rising regulation and competitive pressure reinforces need for increased autobody structure performances : safety, durability, acoustic comfort and weight reduction. Requirement for each car manufacturer to reach a car averaged 140 g CO_2 emission/km in 2008 (CAFE) versus current 160 g/km for ACEA members (Automotive Car manufacturer European Association) induces a target of 100 kg weight reduction for a M1 segment car (Megane type) in which 70 kg concern body in white.

To achieve this objective either new and more expensive materials have to be used (HSS, UHSS, TRIP and hot forming Steels, aluminium), new cost-efficient lightweight concepts have to be developed (mixed materials), and improvements have to be made in assembly techniques.

Even though weldbonding pioneer application was performed as early as the 1960's (Rear body of DATSUN models produced by NISSAN MOTORS), and although adhesive bonding high mechanical potential has been known for several decades : compared to conventional resistance spot welded structure it features elevated static, dynamic, fatigue strength associated to stiffness and NVH behaviour improvement. A renewed strong interest is being currently shown in the use of adhesive bonding and on its associated hybrid fastening technologies (Rivet-bonding, Weldbonding).

A state of art on the mechanical potential and on the applications of adhesive bonding in the automotive body in white (BIW) will presented. Technical stakes of its use in an industrial context will be pointed out, and automotive engineering approach will be presented.

ADHESIVE BONDING APPLICATIONS IN THE AUTOMOTIVE BODY IN WHITE

Although adhesive bonding, first appeared in automotive industry in the last century, its massive development seems to have really started in the last decade. Its is currently massively applied in S segment : around 70~100 m of bonded or weld bonded junctions are performed in BIW of S class Mercedes, Volvo V80, and BMW 7. Its generalisation to all segments is expected. We will illustrate through examples the main reasons leading to adhesive use in the Body In White.

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Body Stiffness Improvement

It consists in using this well-known characteristic stiffness of continuous joined structures[1] (weld-bonding, brazing, laser welding). In a conventional discrete assembled body, the assembled part are not properly linked between two consecutive fasteners, what lowers body stiffness. It can be easily schematised on a closed top hat structure loaded in torsion. The torsion rigidity of closed section near spot welds is high whereas this rigidity is lowered between the spot corresponding roughly to omega shape open profile one. Figure 1 illustrates resulting stiffness improvement when moving from spot-welded structure (hollow symbol) to weld-bonding structure (plain symbol) for different materials/thickness. The observed stiffness gains are high particularly for presented torsion loading, and have also been mentioned for dip galvanised structure and to some extent for spot-welded structures after cataphoresis.

Adhesive bonded or hybrid bonded structure give the opportunity to reach the optimal stiffness of a given design. Their stiffness behaviour is equivalent to monolithic structures of same geometry. It can be evidenced comparing spot welded and adhesive bonded tensile shear specimen. The stiffness improvement does not result at first order from more homogeneous deformation in the substrate planes but rather from geometrical effects. Given the bending behaviour of the specimen, the rigidity improvement is mainly related to reduced bending length outside the overlap (L1 vs L2 cf. Figure 2, and to associated higher lateral extension of the effective overlap zone). So that local deformations at adhesive joint edges have a negligible influence on structure stiffness compared to equivalent monolithic one.

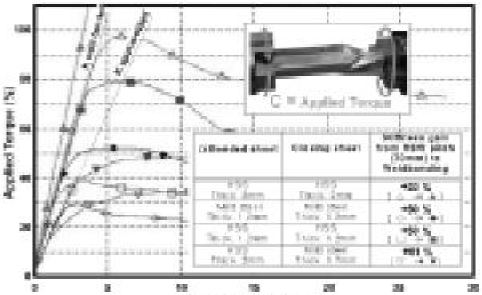


Figure 1. Spot-welded and Weld-bonded structures stiffness comparison.

Even though body optimal stiffness can be reached using "low" modulus adhesives (Young modulus around 200 MPa), their industrial use is not often possible as joint thickness can not be controlled enough to guarantee robust stiffness performance of the structure (gap between parts can not be precisely controlled between consecutive spot-welds, risk of important joint shear stiffness decrease for thick joint).

Applied to a complete vehicle, stiffness

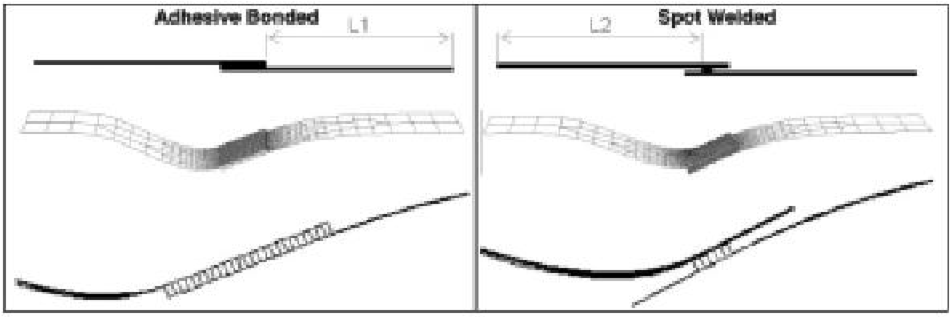


Figure 2. Spot-welded and Weld-bonded stiffness behaviour on tensile shear specimen.

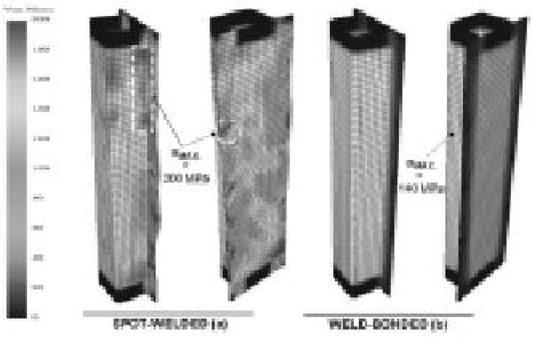


Figure 3. Stress comparison in Spot welded structure(a) and weld-bonded (b).

improvement due to adhesive bonding can reach 20% (+20% for torsion +20% and +13% for bending), it can be use to improve body stiffness of a particular design. this latter property can be transformed into weight reduction at body iso-stiffness (-10%).

Fatigue Life Improvement

Adhesive bonding improves fatigue strength of the part. It results from a more uniform work of the structure induced by continuous bonding : at same loading, stress in a weld-bonded structure are often 30% lower than equivalent spot-welded one as presented in Figure 3 below.

An important attention is currently devoted to adhesive joints to improve conventional assembly fatigue strength. Several order of scale in fatigue life are often gained moving from a classical spot welded structure or riveted structure to adhesive bonded or hybrid assemblies. It can be illustrated regarding spot-weld loading, presence of adhesive bonding between consecutive fasteners acting as additional parallel mounted elements that mechanically unload the welds. Continuous bonding leads to an homogeneous work of the structure and to a reduced supported load per assembly unit length : this explains outstanding fatigue properties of

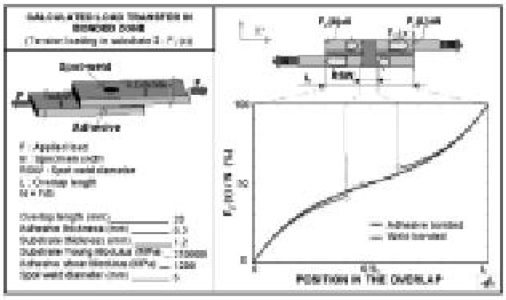


Figure 4. Load transfer comparison in bonded and weld-bonded joints.

bonded components. Compared to RSW, we could again consider that adhesive use, tend to an optimal work of a given conception.

If we still regard applied load on spot-weld, unloading due to adhesive introduction additionally acts in a section passing through the spot weld or rivet itself. This classical property is also evidenced considering adhesive governed hybrid bonding failure behaviour. Figure 4. presents load transfer in bonded and weld bonded single lap joint under tension. Tension loading in a substrate is studied inside a longitudinal cut passing through RSW centre. Results reveal classical non homogeneous load distribution along the overlap in bonded systems with concentrated transfer at joint edges. It shows quite no occurrence of spot-weld in load transfer inside the bonded zone, and finally highlight limited applied load on spot weld in hybrid joint. It can be noted that load transfer between the two fasteners is non linear and can not be estimated considering apparent average shear stiffness of spot-welded and adhesive bonded zones.

The Figure 5 compares load in a spot-weld in similar welded and weld- bonded structures, it sums up aforementioned RSW unloading effects.

There is thus a trend to develop new weld-bonding applications in advanced development phases to reduce fatigue failure

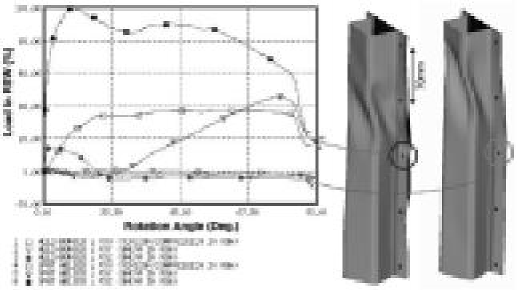


Figure 5. Load comparison in RSW for welded and weld-bonded structure.

risk in the conventional assemblies. It sounds like a preventive use of adhesive bonding for RSW fatigue reinforcement while it was generally used, in last development stages, as a curative solution to spot-weld failure.

Dynamic Behaviour

As it has been mentioned earlier adhesive bonding permit to reach optimal stiffness of a given design. It results in an improved structure dynamic behaviour. Figure 6. compares a sub-system assembled by either by RSW (crossmember) + arc welding (sidemember/crossmember) (a) or by Weld-bonding (crossmember) + adhesive bonding (sidemember/crossmember) (b). The four first resonance modes are presented. It is highlighted that adhesive joining use leads to elimination of some natural frequencies (e.g. crossmember beating) and similar mode shift toward higher frequencies. Even though the deliberated choice of both crossmember weld-bonding + sidemember/crossmember adhesive bonding is aimed to drastically underline this effect.

If stiffening effect induces natural frequencies shift toward higher frequency, it simultaneously reduces inertances of the structure at load entry point as it can be seen on curve below (Figure 7 resulting in iso-stiffness reduction). The adhesive bonded structure better noise vibration behaviour is sometimes attributed to damping behaviour of the adhesive.[2] In fact, it mainly lies on stiffening induced effects. The use of adhesive intrinsic viscous properties to reduce body noise behaviour appears doubtful, as it necessitate high energy deformation in the joint (low modulus and high joint thickness) which is not compatible with industrial application and reasonable strength. If such effect can be observed on specimen,[3] they are not significant on structures : in case of panel vibration (e.g. dash panel) possible dissipated energy in the joint is clearly negligible compared to panel vibration energy. Whereas use of classical elastic rigid adhesive often permit to reduce transfer from load entry point to these aforementioned panels (-4dB).

Static and dynamic strength potential use

According to ISO 6354 structural adhesive definition, the strength notion is implicit in structural bonding definition. Normally, addition of adhesive bonding in body should not be sufficient to employ "structural bonding" terminology as long as role of adhesive in the structure integrity and adhesive strength based design is not considered. To this point of view, if structural bonding is said to be an old technology in the automotive field, a few really structural applications have ever been developed. In a similar manner, it is sometimes argued for a need for new terminology (highly structural adhesive) whereas a proper use of consecrated semi-structural and structural bonding existent mechanical definitions should be entirely satisfying.

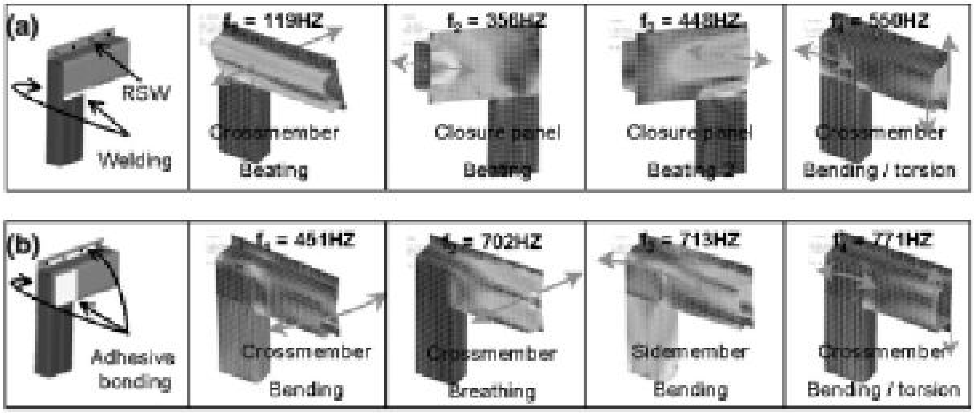


Figure 6. Natural frequencies comparison of a welded (a) and adhesive bonded (b) part.

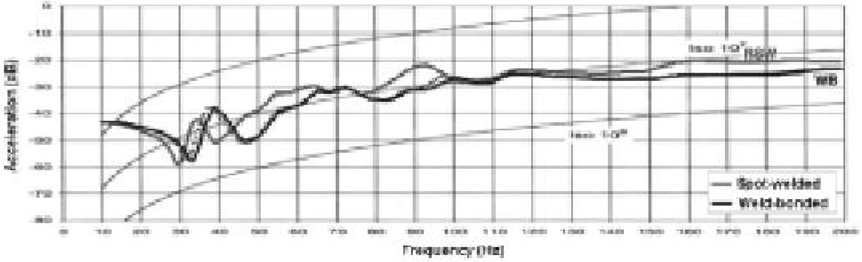


Figure 7. Comparison of dynamic behaviour of spot-welded and weld-bonded structures.

State of art and interests

Structural bonding high static and dynamic strength potential compared to RSW or riveting is a well-known property. As it can be seen on Figure 8 and 9 strength gain can exceed 60% compared to discrete fasteners. It is induced by more homogeneous work of the structure and high intrinsic resistance of the adhesive (when submitted to appropriate loading mode).

Apart in higher adhesive resistance due to better adhesive thickness control, which is generally provided welding pitch reduction on industrial structures : there is no synergistic effect between adhesive bonding and spot-welded strengths in a hybrid assembly (obviously hybrid assembly failure load adhesive one + spot weld one, cf. Figure 4, 9). Nevertheless some kind of synergy appears considering ruining mode : presence of spot-weld featuring higher peel resistance prevent delamination mode propagation as it can be shown in Figure 10.

There is a natural demand in automotive engineering toward adhesive use to solve plug failure problem, sometimes in latter development stage or to integrate this higher efficiency early in the development to improve safety or reduce weight (steel and high performances aluminium/steel assemblies). Regarding the BIW, many applications could be foreseen (Figure 11, red parts), and its extension to all superstructure with subsequent gain can even be planned.

Structural bonding application technical stakes

The use of adhesive strength potential represents the most important technical stake. It necessitates the technical capacity to use adhesive bonding as a

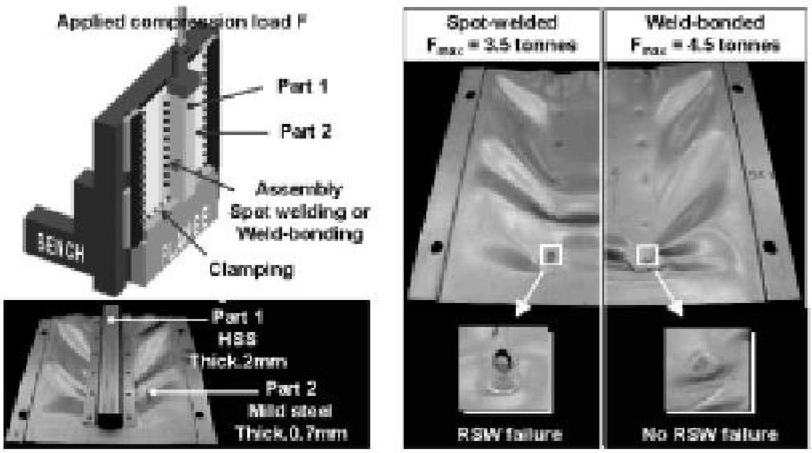
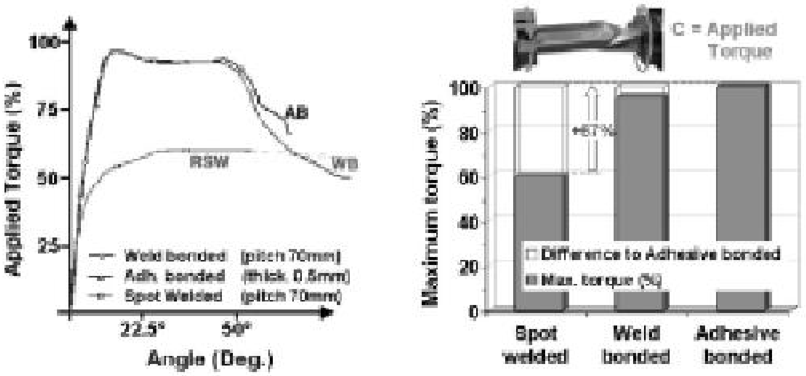
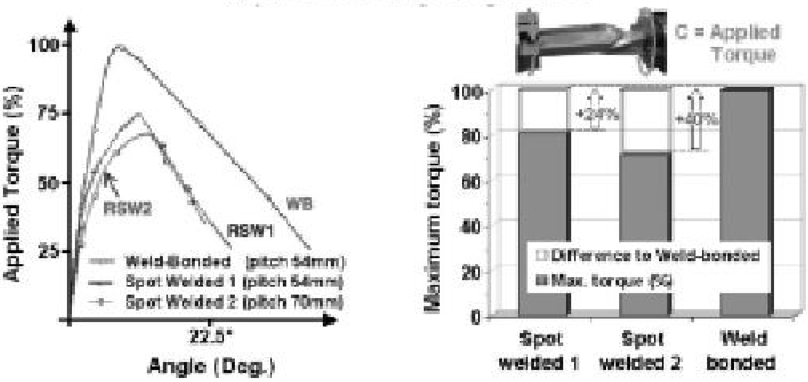


Figure 8. Static strength comparison of welded and weld bonded structure under compression.



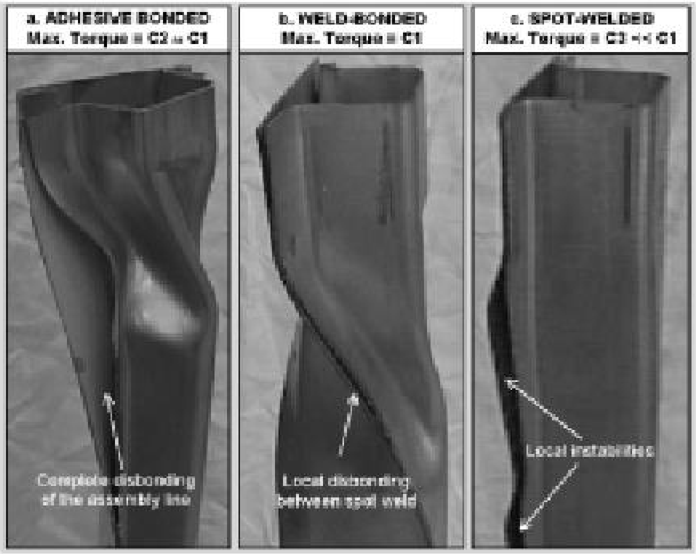
(a) 1.2 mm thickness mild steel



(b) 2 mm thickness High Strength steel

Figure 9. Static strength comparison of welded and weld bonded structure under torsion.

structural fastening technology what is not currently true, even adhesives are used in automotive structure since a long time. For such actually structural applications, the ageing problem really becomes crucial as it directly condition the targeted strength performance. Second, if gain on stiffness, NVH, fatigue provided by adhe-



a. Even though similar maximum torque are achieved (C2 ≈ C1), important difference in ruining mode. a. = Catastrophic failure : delamination mode propagation due to inherent adhesive poor peel strength.

b. RSW stops delamination failure mode propagation.

c. characteristic punctual assembly behaviour, apparition of local instabilities at "moderate" loading reducing structure efficiency and preventing achievement of high loads levels

Figure 10. Compared failure behaviour depending on fastening technology.

sive bonding can be estimated quite easily using commercial software, strength calculation tools compatible with engineering practices and operational in industrial modern development logic still have to be developed. What can not be assessed simply as soon as "edge effect modelling" is required.

We will first point out the industrial problem posed by structural bonding (failure) modelling and illustrate Renault's work through example. Then we will illustrate characteristic automotive engineering approach carried out to secure adhesive bonded structure design toward ageing.

Structural bonding (failure) modelling

If perfect (indestructible) bonding modelling do not represents any technical difficulty using commercial codes they obviously do not always correspond to reality. Engineers can not reasonably base body conception on an a priori hypothesis that bond will not fail. Continuous bonding modelling failure prediction nowadays represents a major stake for car manufacturer wanting to give itself the real opportunity to implement this assembly technology. It constitutes a normal prerequisite to technical credibility on every structural fastening technology and is reinforced by modern numeric development schemes.

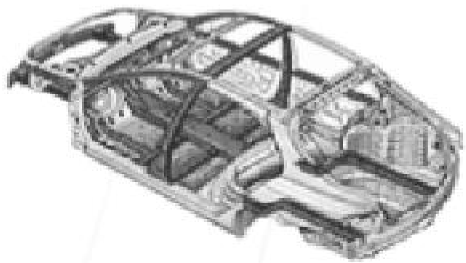


Figure 11. Structural bonding (strength) potential applications.

Industrial use of structural bonding requires capacity to predict adhesive strength, implies stress/strain analysis of the joint and associated failure criterion definition. Work in this field also start in the last century with stress analysis in single lap joint developed by Volkersen[4] and Goland.[5] If these analytical closed-form methods are limited because only simplest joint geometries and boundary conditions can be accommodated, they highlight the main concepts governing adhesive joint failure. They evidenced respectively non homogeneous stress distribution in joint overlap, subsequent high shear stress at overlap edge and presence of critical tearing stresses in this zone.

But automotive application often implies complex structures and consequently approximated numeric design methods. We will focus on the Finite Element methods (Finite Difference are not used in industrial mechanical analysis). These latter method have interestingly taken advantage of particular properties of some body featuring a small dimension compared to others. Making physical assumptions, (compared to tridimensional model, e.g. Kirchoff-love plate model) the global behaviour of the body can be reproduced by taking into account first order phenomena which are critical toward design. With adhesive bonding (as for composite materials) due to material properties discontinuity and particular geometry, local phenomenon become crucial and govern design. So called edge effect modelling constitutes central aspect of structural bonding design.

Considering implicit models, a discretisation of the structure at joint edges can be carried out (to some extend = limitation due to CPU time) for a better approximation of stress/strain field. Keeping in mind stress that elastic based failure analysis can only be performed comparatively using same meshing element type and size, as stress absolute value have no significance because of stress singularity at interface corner. To be more rigorous, a proper analysis of stress field in adhesive bonded structure would require use of special interface element. In commercial code classical finite (displacement) elements do not satisfy stress vector continuity through the interface (but only displacement continuity). Some special interface element have been developed[6] (mainly based on Reissner's (mixed) variational principle but differing from resolution method). Another interesting methodology have been provided by asymptotic expansion method which combine advantageously efficiency of FE plate analysis with rapidity and power of analytical perturbation method.[7] The stress field in the bonded zone is constructed through a asymptotic sequence, stress boundary condition are extracted from a plate FE calculation. Apart from gain on calculation time, main theoretical advantage lies in fulfilment of stress boundary condition, which is a crucial point in edge effects. To be exhaustive, fracture mechanic design methods must be mentioned, they can reveal as efficient as analytical closed form approach for simple specimen. Nevertheless, their validity and their interest for industrial complex loading and complex structure remain to be proven.

Given this theoretical overview of the mechanical problem posed by structural bonding modelling, we must had industrial calculations constraints which complicate resolution, mainly for crash modelling (explicit models). Indeed, typical element size is around 10 mm with generally two maximum plate element across the joint overlap, What do not allows to access physic failure governing parameters. Figure 12 below illustrates technical challenge provided by adhesive crash modelling in these conditions. It presents calculated stress distribution across the overlap using typical edge effect analysis adapted FE modelling (300 2D special elements, size < 1 mm), and equivalent acceptable industrial model (8 elements, size $\approx$10 mm).

Keeping in mind that only legitimate objective for R & D work is to permit a

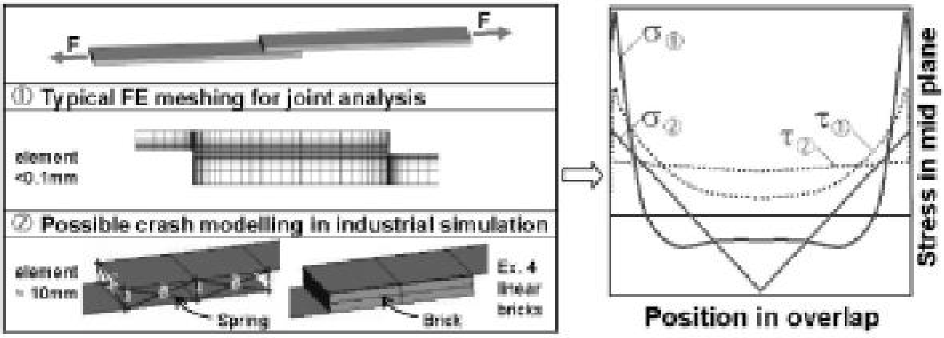


Figure 12. Adhesive modelling stakes, models performance comparison.

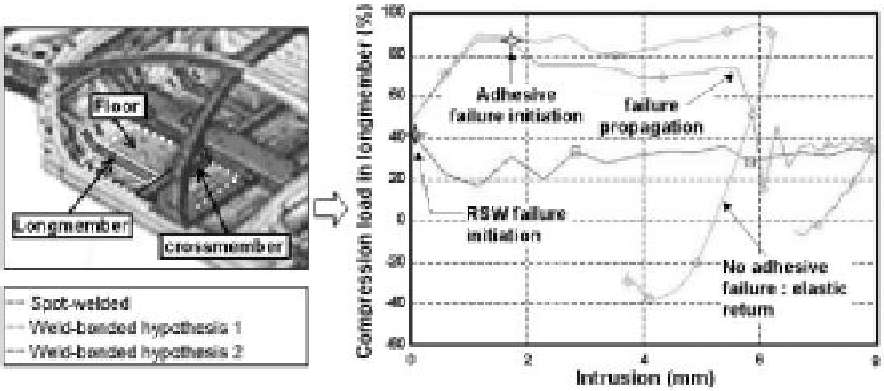


Figure 13. Vehicle crash reinforcement by structural bonding.

new technology to be integrated in vehicle development projects. Calculation tools developed must obviously be operational inside these latter ones. Research of solution to structural bonding modelling problem must be completed in this restrained perimeter of industrial calculation. It must keep the widespread explicit calculation base and fixed industrial meshing/calculation time, technique for resolution "edge effects" modelling (theoretical basis, element, meshing rules, failure criterion) is the adjustment variable and not the reverse. This philosophy was the guideline of Renault R & D approach, it imposes to consider adhesive modelling in a quite new angle, in a necessary shortened perimeter compared to numeric method power potential.

Figure 13 Below presents structural bonding modelling application for crash reinforcement. Plug-off problem bas been observed between longmember/floor spot welded assembly. Two kind of Adhesive bonding reinforcement have been tested (hypothesis 1 : longmember/floor+crossmember/floor hypothesis 2 longmember/floor). Hypothesis 1 performs lower than hypothesis 2. It is due to over-stiffening near crossmember, what induces sequential loading of the bonding with stress concentration in this region, and consequently lead to adhesive failure. Whereas in hypothesis 2, structure and bonding work homogeneously what permit to solve RSW failure problem. It finally permits weight reduction as alternative welded solution would request extra reinforcement part.

Industrial problem of structural bonding crash modelling has required a specific approach (which philosophy was initiated by asymptotic method previous work[7]). It aims at providing the best resolution in a restrained perimeter of industrial calculation. It illustrates way in which problem of introduction of new fastenning technology (adhesive bonding, laser welding) is set to automotive enginneer.

Structural bonding ageing mastering

It is often claimed that adhesive bonding is not used due to fear toward its ageing behaviour, and argued for a need to develop new ageing test to rise this "key" problem : what "obviously" remains useless as long as their exploitation stays comparative. A real breakthrough in structural bonding industrial use do not depend on separated resolution of two main aforementioned mechanical or physico-chemical problems. Indeed, exact resolution of the mechanical problem using standard FEM do not interest automotive engineer because it can not be use on industrial model : as for development of new more representative ageing test in regard with the already important existing ones. Every approach attending to improve/treat only one aspect of the problem will not provide the expected step forward. Core aspect of the industrial problem rather appears in an approximate solution of a global system than in an exact resolution of separated physico-chemical and mechanical equations. It requires to build up homogenous skills in several fields and capacity to synthesis them in order to master final performance. In this way, automotive engineering would prefer focusing on establishment of a mechanical exploitation of a conventional ageing test (even though stringent nor very accurate) to make a rational integration of adhesive ageing in the design. Only this procedure allows to predict and secure final strength performance, its real final engineering purpose. From automotive industry point of view, the key step conditioning technology maturity and related breakthrough in its use lie really on this engineering capacity in gathering and synthesising different skills.

Figure 14 illustrates pioneer work performed toward a rational integration of adhesive ageing loss performance in bonded structure design. It covers an industrial case where adhesive bonding has been evaluated for crash reinforcement

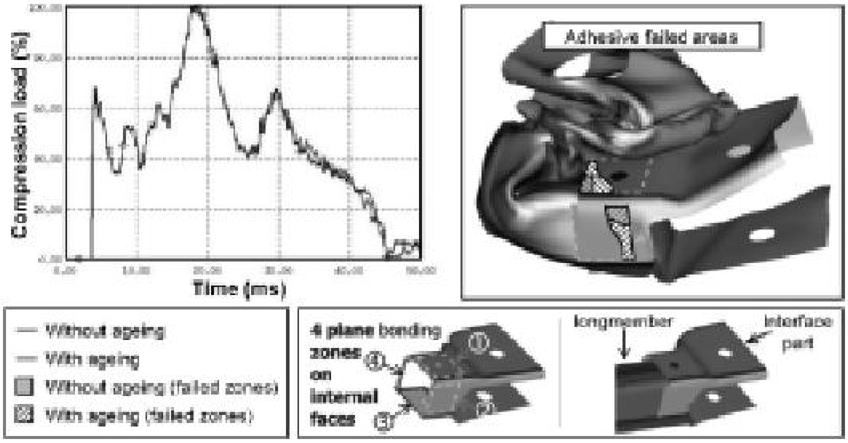


Figure 14. Crash behaviour of a bonded assembly before and after ageing.

of a bolted assembly between a longmember and an interface part. Results shows that structural bonding has totally fulfilled his function, both with or without ageing. Even though adhesive local failures are observed, they appear in the ultimate stages of the crash (induced by cleavage when parts come in contact). The main fact is the achievement of sufficient strength even after ageing, permitting to undergo first high load peaks.

The employed methodology consists in determination of failure criterion parameters and adhesive properties after ageing using humid cataplasma test. The ultimate purpose is not an utopic full-numeric approach aiming at a total elimination of experimental validations (even though all car manufacturers expect to reduce them drastically according to new development logic). This methodology, based on FE tools, simply seems to be the most natural one to structure conception methodology. It permits to secure design toward ageing, putting in relationship mechanical need on the part with adhesive ageing behaviour (and adhesive ageing specifications).

CONCLUSION

Current renewed interests on adhesive bonding is driven by need for improved BIW performances. We have pointed out adhesive bonding particular property to provide an optimal mechanical work of a given conception (drawing) with related stiffness, NVH and fatigue behaviour improvement. Combined to the fact that it well accommodates with classical spot welded design (contrary to laser welding where specific drawing is required, more impacting on engineering practices) and to its industrial process high productivity : its real implementation in automotive industry and its generalisation to all segments is now expected.

Even if structural bonding is often said to be an old technology in the automotive field (indeed NISSAN pioneer massive application dated from 1960's), few really structural applications have ever been developed. The use of adhesive strength potential, even inherent to structural bonding mechanical normal definition, constitute a technical stake of another order. Renault voluntary demarch aims at challenging it to provide new cost-efficient solutions for safety improvement and weight reduction. It requires an effective mastering of structural bonding technology, i. e the capacity to perform a systematic and secure use of its promising strength potential, where "edge effect" modelling problem naturally appears, and ageing problem takes a really crucial importance.

Renault R & D guideline, in front of adhesive strength modelling problem "obviously" postulate that developed tools must be operational in engineering development project, what singularly complicate resolution of this mechanical problem and drive the need for new calculation approach (to some extend solely initiated with asymptotic expansion method based tools). Promising modelling results for structural bonding crash reinforcement on industrial sub system have been presented.

Regarding ageing problem, often considered as a blocking point in structural bonding development, it has been pointed out that, from the automotive point of view, problem firstly stands in capacity to integrate this phenomenon in the design rather than in development of new more accurate ageing test. Only this approach permits to master adhesive strength, the final engineering purpose. In a more general way, the key step conditioning technology maturity and related breakthrough in its use, lie in engineering capacity to conduct a really pluri-disciplinary and global approach. It stands in the development of coherent skills in several different fields and especially in the faculty to organise and synthesis them to provide the best approximate response to a system rather that in resolution of particular aspects taken separately.

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