Joint solutions in constructive elements made of composite materials

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ABSTRACT

For a long time, the construction sector has been one of the more conservative sectors, and has included society’s new technological discoveries at a very gradual rate. On many building sites the same building procedures as those used 50 years ago are still habitual, and the probability of change is doubtful.
The use of composite materials as constructive elements in buildings seems to be one of the developments which is being introduced in this sector. In fact, some constructive elements made of composite materials are plainly visible, such as facades, coverings, structural elements, coatings, partition walling, etc. These elements are used, however, in a limited and occasional manner.
One of the main problems in the use of these materials is the joint method. Research in assembly methods is limited (in comparison with other materials), showing severe problems when different composite materials need to be assembled together, or when composite materials need to be bonded with traditional materials (such as concrete, steel, etc.). The results of the analysis of these bonding problems are given in this article, as well as some possible solutions which are shown with their advantages and inconveniences.

RESUMEN

Históricamente, el sector de la construcción ha sido uno de los más conservadores y que más lentamente ha asimilado los avances tecnológicos de la sociedad actual. En muchas obras aún se están usando los mismos métodos y materiales que hace 50 años, con pocas perspectivas de cambio.
Uno de los cambios que parece empezar a penetrar en el sector, es el uso de materiales compuestos para elementos constructivos de los edificios. Así se pueden empezar a ver fachadas y cubiertas de materiales compuestos, elementos estructurales, revestimientos, divisiones interiores, etc. Estos normalmente se aplican de forma aislada y esporádica.
Uno de los principales problemas que presenta el uso de estos materiales es los sistemas de unión. Estos sistemas están poco estudiados (comparado con otros materiales) presentando serios problemas en el momento en que se quieren unir diversos elementos formados por composites, o bien por composites y otros materiales considerados como tradicionales (hormigón, acero, etc.) En el artículo se recogen los resultados del análisis de los problemas de estas uniones y se presentan posibles soluciones con sus ventajas e inconvenientes.

1. INTRODUCTION

An ideal structure should be designed without joints, since joints are a potential source of weakness and an additional weight. In practice, however, the upper limit to component size is determined by two fundamental factors. These factors are processability and facility in transportation and assembly. Therefore, most structures require joints to transfer loads between parts. The joints can be between similar or dissimilar materials, but in this paper only the former are studied. Composite material frames accept metal frame connection methods such as adhesive (Messler,1993), discreet mechanical fasteners (Matthews, 1987) and welding (Grimm, 1990; Howie et al.,1993), considering differences between materials. Even though some tendencies can be established, behaviour of a certain composite material is not usually possible to generalise. Aelotropics and strength, interlaminar low shear resistance and traction resistance along thickness, generate unexpected failure modes.

Considering all these factors involving traditional composite joining, and new methods being investigated, like integral fit joints (Lee and Hahn, 1997), a survey of the advantages and drawbacks of each method will show the optimum assembly system for composite frames. Structures involved in this paper are made with FRP (Fibre reinforced polymer) standard profiles actually available in the construction market. Their most important features and benefits are Corrosion Resistance, Low Conductivity - Thermally and Electrically, Non-Magnetic Electromagnetichal Transparency, Lightweight, High Strength, Dimensional Stability and Low Maintenance. These characteristics make possible an easy manipulation of the profiles, allowing joint procedures that would not be workable with traditional profile materials (concrete or steel).

2. STRUCTURAL JOINING TYPES IN FRP INDUSTRIAL BUILDINGS

Practical composite frames are formed by several simple profiles joined together to form a resistant unit. This whole would only be effective if a perfect stress transmission from part to part is guaranteed. From all joint types of an industrial building, it would not be correct to make a classification according to their importance, for the failure of any of these assemblies would cause a total or partial failure of the structure. Therefore, it is important to have all joints perfectly solved. However, a simple classification can be drawn up, but must consider the infinite angles of incidence and the multitude of load factors that can arise for each part of the classification. That distinction would be: beam-column, column-column, beam-beam and column-footing joints. In frames used for traditional industrial buildings, nearly all structural joints are affected by sheer stress and both tensile and compressive stress provoked by flexure momentum.

3. JOINING METHODS FOR COMPOSITE PROFILES

Adhesive, thermoplastic welding and discreet mechanics are the most common techniques utilized to join composites. Other methods like integral fit joints are being investigated as possible possibilities for an alternative structural assembly method (Fig 1). In this part of the paper, a short explanation of each method will be given.

3.1. Adhesive Joints

Structural bonding of assemblies using adhesives is a rapidly emerging technology in many industries, especially throughout the composite industries. But its use for structural joints in buildings needs to be questioned because of adhesive low resistance when affected by peel or tensile stress. With adhesives, there are a multitude of rules and tests that must be followed for a successful transition. If these rules and tests are not followed correctly, the failure potential during this transition is great. In building applications, the result could be catastrophic and very costly to the manufacturer. Therefore, despite the existence of some guides, designers and engineers should rely on adhesive manufacturers as the experts for some aspects.

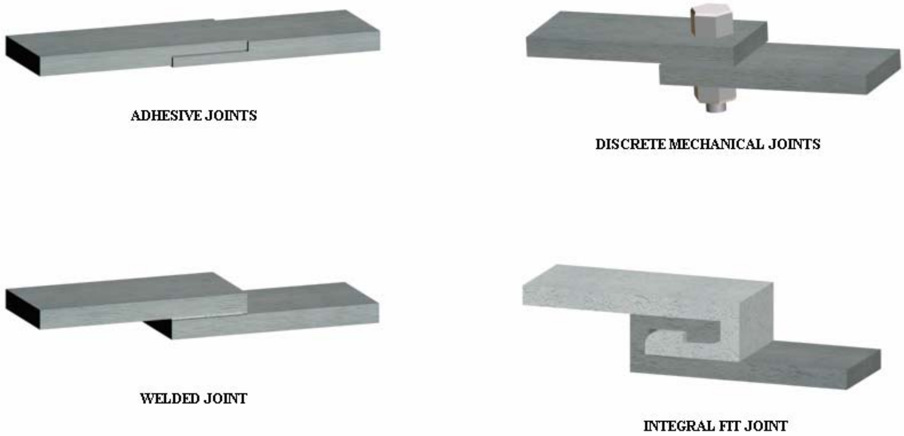

FIGURE 1. Joint technologies for composites.

Designing a joint to accommodate an adhesive and the type of adhesive is based on numerous factors. The most important factors are how well the adhesive bonds to the entire substratum, what its physical properties are, and what kind of a joint is designed. Next, one must ensure the adhesive can handle the temperature, environmental, and stress conditions to which the structure will be exposed. After these considerations, the designer can then look at the working and fixture times of the adhesive. Finally the colour and other aesthetic considerations must be met (Parker et al., 2001).

The most common structural adhesive systems used in composites to date are Polyurethane, Metacrylate, Epoxy, Wet Tabbing, Putty and Adhesive tapes. From this list, polyurethane, metacrylate, epoxy and pressure sensitive tapes present best performance for high stress structural applications. Polyurethane comes in one part and two part systems. One part's mechanical properties are lower than two parts system. Their most important drawbacks are the dependence on atmospheric moisture to catalyse (therefore they are not recommended for dry atmospheres), the presence of dangerous components and the need of surface preparation on most composite materials.

Methacrylate usually comes in two part systems, and its mechanical characteristics are great. It does not need surface preparation in many cases and has good adherence to a wide range of substrata.

Epoxy adhesives come in both one part and two part systems. One part system needs heat to cure and later refrigeration, which makes the assembly process more complicated. Two part systems are room temperature curing. However, booth need surface preparations and have poor flexibility.

Finally, pressure sensitive tapes, are almost new in some composite sectors, and their main advantage is instantaneous adhesion. On the other hand, they can only be used for structural applications in combination with other adhesives of a greater mechanical performance. Each of these systems has its advantages and disadvantages. Adhesive bonding is strictly a surface phenomenon and it is the surface being adhered which determines bondability. The most common stress types a designer or engineer can potentially encounter in buildings are tensile and compressive forces, shear, cleavage and peel. And the most common joint designs are plain lap shear, double lap shear, bevelled lap shear, scarf butt joints, double butt lap joints and stiffeners (Fig 2).

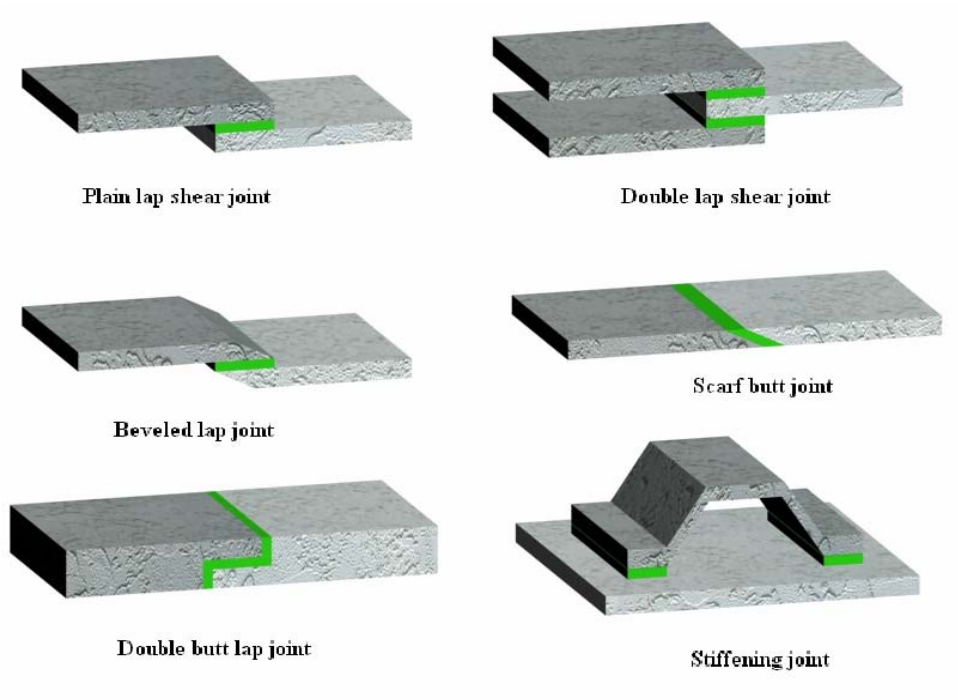

FIGURE 2. Adhesive joint types.

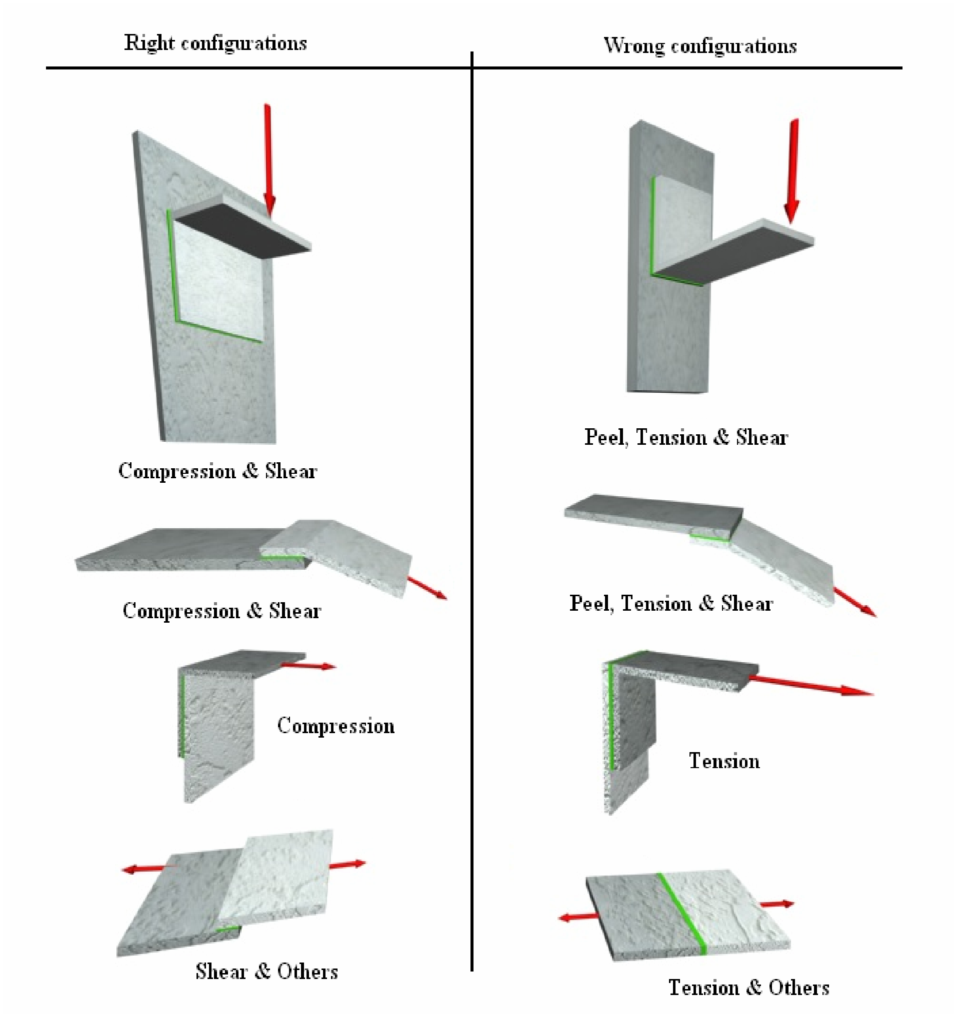

FIGURE 3. Adhesive joints configurations.

When converting two similar or dissimilar materials from more conventional methods of joining to effectively using structural adhesives, one has to consider the following design variables prior to bonding (Parker et al., 2001): Joint design/Bond Assembly, Required Assembly time, Surface preparation, Thermal- expansion of dissimilar materials, Confirm yield stress and desirable failure mode and Cost effectiveness.

Once the structural adhesive is chosen, adhesive joint design is the first variable to evaluate. An effective joint highly depends on good knowledge of the stress applied to the assembly. Three types of stress are tensile, shear and peel.

Pure tensile situations in adhesive joints are only possible in ideal joints because the adhesive flexes provoking shear stresses. However, almost pure tensile joints can occur when two parts forming a sandwich are joined. The performance of adhesives under tensile stress depends on the flexibility or rigidity within the structural adhesive chemistry. The best performance of adhesives is when shear stress is applied.

Peel strengths are lower than shear strengths because the point of failure is limited to the edge of the bond and less force is required to propagate a failure once initiated.

3.2. Discreet Mechanical Joints

Mechanical joints are the ones that use discreet fasteners like bolts, pins or cramps to assembly two or more parts. To make a mechanical joint, drilling a hole in both parts is indispensable, and it provokes fibre cracks and stress concentrations. However, mechanical joints offer very high resistance and efficient assemblies, and bolted joints are the most frequently used for joining FRP material frames. Therefore, this part of the paper will be centred on bolted joints.

Bolted joints' performance depends on a multitude of factors. A joint can be influenced by the type and shape of the fibre (single direction, weave, etc.), resin characteristics and volumetric percentage of fibre and so on. Moreover, joint toughness is determined by assembly type (one lap, two laps, etc.) and the geometry, joint dimensions, washer size, torque, hole size and tolerance. The torque translated into a force applied towards thickness becomes a crucial factor.

There are four failure modes affecting bolted joints, and one affecting bolts (Figure 4). If it is impossible to secure all failure modes at the same amount of load, bearing failure would be preferable, due to its non catastrophic failure. There are three failure planes: bearing (0º), tension and shear-out (90º). Radial compressive stress is highest near to the bearing failure plane, tangential tensile stress is highest near to the tension failure plane, and shear stress reaches its peak value along the shear out plane.

When designing a bolted joint, one must consider diverse factors to create a successful joint. The influential parameters are Geometry, Load directions, Load types and Bolt torque.

The less isotropic the FRP part is to join, the more importance is given to load direction factor. When a bolted joint is designed for aelotropic materials, one must try to make load direction coincide with maximum strength direction of the composite element. Assemblies that are compression-loaded are not sensitive to internal geometry changes, and are more resistant than tensile-loaded joints. However, tensile-loaded joints can be approximated to compression-loaded ones for great E and W values.

Another aspect to consider is load's type, but in construction only static loads usually affect the structure, and bolted joints are not barely sensitive to static load changes.

After all, and when a design method has been applied to calculate geometry, only the assembly construction is left. When constructing a bolted joint, drilling is necessary, and tolerance between bolts, holes and washers will occur. To maximise assembly strength, tolerance levels have to be the minimum possible. Then, when bolts are positioned, the torque applied to the bolt has to be as great as possible.

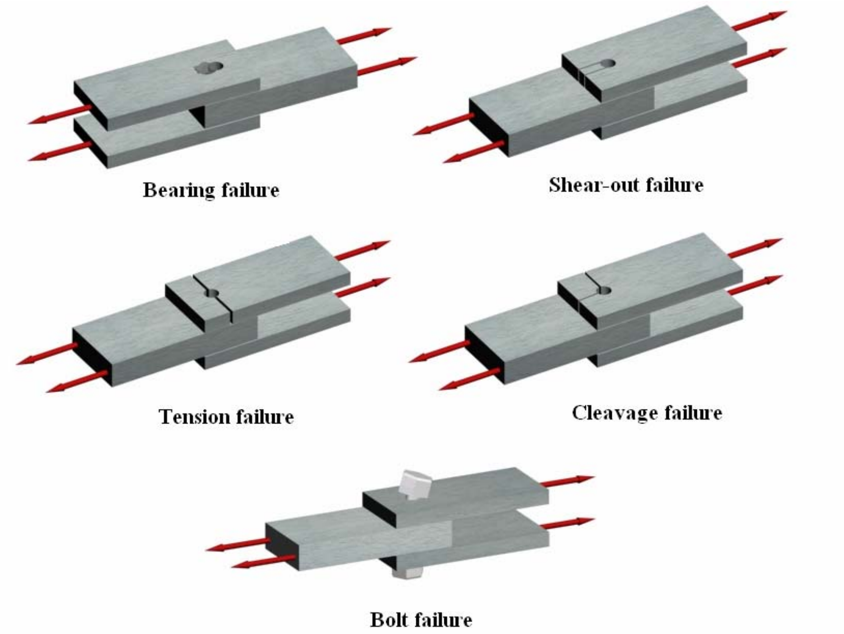

FIGURE 4. Failure modes in bolted joints

3.3. Integral Fit Joints

An integral fit joint can be identified as a locking joint between two or more components. The joint surfaces in contact depend on how the individual components were designed and manufactured. The joining itself is held together by material interference of the surfaces in contact. This type of assembly connection differs from others where additional material (such as discreet fasteners or adhesives) would be required to hold the parts together once the joint contact configuration condition is established. This technique permits a special design for every type of joint, optimizing it for its needs in every load situation. Therefore, application of integral fit joints in construction would provide many advantages if a great design was found. Assembly time could be reduced and mechanical properties improved.

3.4. Welded Joints

Plastic welding is a joint technique that is potentially able to create an assembly with the same properties as the adherents used. These properties include mechanical performance, but only when referred to non reinforced polymers. Welding composite materials is different, because of the small lack of fibre reinforcement continuity. However, mechanical behaviour is great. Even with the advanced welding techniques in existence, most require precision, good knowledge of the technique, and a range of special tools to be manufactured. All this become a considerable drawback when assembly has to be made on site. On the other hand, all welding joint methods imply some important advantages, such as non additional weight to the structure, non additional material and no need of surface preparation. To weld together two parts, an external influx of energy must be provided, and according to the way this heating energy is generated, four welding methods can be distinguished. These methods are Bulk heating, Frictional heating, Electro-magnetic heating and Two stage techniques.

'Bulk heating' techniques are available for performing co-consolidations. This may be considered an ideal joining method because no weight is added to the final structure, no foreign material is introduced at the bond line, essentially no surface preparation is required, and, most importantly for construction, the bond strength is equal to that of the parent laminate. On the other hand, the entire part is brought to melting temperature, and this implies complex tooling to maintain pressure on the entire part to prevent deconsolidation. And that is a very important drawback making it quite impossible to be used for construction.
'Two stage' techniques are not suitable for the construction sector, because they use thermal conduction of the material for heating transfer. This makes it a long process for polymers because of their low conductivity. Also, the difference of temperatures created between the surface and the interior, and the high pressure required to consolidate the bond line, may cause warpage flow in the hot inner region.
Ultrasonic welding (thermoplastic is brought to melting temperature by ultrasonic vibrations), pertaining to 'frictional heating', and Induction welding (thermoplastic is brought to melting temperature by an induction system) and Resistive welding (an electrical conductive mesh is located between surfaces, bringing thermoplastic to melting temperature), pertaining to 'electromagnetic heating', are the most promising welding techniques. They present common benefits. In these techniques, only the welding interface is brought to melting temperature, minimizing the impact on the rest of the structure. Also, welding times are very short and large scale welding may be performed through sequential approaches. And finally, they all include the possibility to perform on-line monitoring of the consolidation. On the other hand, they have all the general drawbacks of welding joints, commented at the beginning of this paragraph.

4. COMPARISON

First table compares assembly operations and the relative total cost of all techniques (Table 1). Table 2 compares performances in front of strength and environment (external conditions), and shows the possibility to join two different materials.

Assembly operation						**Assembly cost**
Joint type	**Surface preparation**	**Joining previous operations**	**Joining operation**	**Joining time**	**Join work Security**	
Adhesive joints	Most adhesive need cleaning and other preparations	None	Impregnate Surface with adhesive and press together	Adhesive cure time	Some adhesives contain harmful components. Fibre cutting	Cheapest
Bolted joints	None	Drill holes for bolts and align parts. Set fastening.	Insert and cinch fasteners	Cinch time per bolt.	Fibre cutting.	Medium
Welded joints	Surface clean, and just some methods need another surface preparation.	Some methods need previous tool setting.	Apply heat method	Heating and cooling time	Heat is applied	Most expensive
Integral fit joints	Surface clean.	Set fastening	Align components and press together	Press together time	---------	Medium

TABLE 1. Comparison assembly operations

	Strength				General	Environment	Materials joined
	Tensile	Compression	Shear	Peel			
Adhesive Joints	Low	Very high	High	Very low	No stress concen. Low efficiency. No additional weight added.	Corrosion resistant. Problems with high temperatures.	Similar and dissimilar
Bolted Joints	High	Very high	Medium	High	Stress concent. because of bolt holes. High efficiency. Aditional weight added.	Possible corrosion problems if bolts are metallic	Similar and dissimilar
Welded Joints	Medium	Very high	Medium	Medium	No stress concent. Low efficiency. No additional weight added.	Corrosion resistant.	Similar
Integral fit Joints	Depends on design	Depends on design	Depends on design	Depends on design	Additional weight added.	Good performance	Similar and dissimilar

TABLE 2. Comparison performances in front of strength

5. CONCLUSIONS

In practical composite structures, and especially in industrial building structures, all the factors of the comparative tables are very important when deciding a joint method. An ideal method would have nice results in front of all these factors, but that does not occur in the techniques studied, because all methods present some undesirable characteristics. Therefore, if the totality of assembling configurations for an industrial building, need to be successfully covered, the method chosen will have to be a combination of two of the existing techniques. But previously to the decision, of two techniques together, an individual valoration of each method will be exposed.

- Welding method is not suitable for structural applications due to its high cost, its assembling difficulty at work place, and its incompatibility in the combination with other methods, when a lack in welded joints performance needs to be covered.
- Adhesive joints global performance is great, but their tensile and peel strength is very low. Thus, it needs to be combined with another method, when tensile or peel loads affect the joint. Moreover, when joint’s accessible surface is small, adhesive is not valid due to its low efficiency.
- Bolted joints method is probably the greatest, but it has some lack in its performances, as the rest of the techniques. Its principal drawback is the apparition of stress concentrations. This fault, can be critical for high load applications, and should be eliminated. Therefore, a method able to distribute shears better than bolted joints, should be combined with it.
- Integral fit joints can probably become better than the rest of the joining methods, but they are not enough developed for building structure applications. However, a great future study and design of this technique for industrial buildings would mean a reconsideration of this comparison.

At the end, analyzing the comparison tablatures, bolted joints offer better performance than the rest. After this, covering the performance lacks of bolted joints is the only thing left. Looking for compatibilities, one can see that a hybrid joint between adhesive and bolts is probably the best choice. The advantages of this combination added to individual methods benefits are High efficiency due to bolted joints, Great stress distribution due to adhesive joints and Better strength performance.

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