Bonded repair of composite structures in aerospace application: a review on environmental issues

S. Budhe

M. D. Banea

S. de Barros

MEM426 Report Summary

By: Rhys Kawaguchi

Abstract:

The aerospace industry has targeted the use of fiber reinforced polymer composites for the repair of existing structures because of its structural and economical advantages. Because the long term durability of composite repair bonded joints brings up many concerns, this article reviews research done in this field as well as the research regarding the effects of environmental effects on durability. Temperature and moisture and their effects on composite bonded joints are reviewed in depth, as they are the two largest environmental factors applying to the aerospace application of these materials. The article highlights analysis methods, key findings, and future research topics necessary to provide high quality and economical composite repair bonded joints.

Problem Statement:

The main issue this article is targeting is how to assure the long term durability and service life of composite repair bonded joints in the face of environmental factors. This must be achieved in an economical sense while also being extremely time sensitive. Because of the introduction to heavy use of composite material in new aircraft, the aerospace industry as a whole is not well prepared to handle the aircraft secondary structural component maintenance. The complete absence of long term data resulting from environmental effects as well as autoclave availability issues, combine to make this a difficult problem to solve even utilizing modern day technology. The end goal is to produce a repair method utilizing composite bonded joints, with extremely high quality while maximizing process efficiency as well as minimizing the repair cost.

Approach Analysis:

In particular, this article scrutinizes two specific environmental parameters, which are temperature and moisture. Both of these factors have the ability to modify a composite structure’s strength and in turn reduce the active service life. Moisture absorption by composite bonded joints varies according to several factors, including: exposure time, composite laminate, and adhesive material among others. The article first evaluates the product of extreme temperature variation on adhesives, composite materials, and adhesive joints.

Because of the enormous temperature range that must be withstood during aerospace application, adhesive systems with both the capability to resist high temperatures and a high maximum strength are sought after. Among such adhesives are epoxies, ceramics, silicones, phenolics, etc. The priority for such adhesives as applicable to bonded joints, is the ability to maintain static mechanical properties while undergoing serious temperature changes. Studies show that for different adhesives, the tensile strength property of the adhesive itself varies with temperature (Fig 6). From the figure it can be obtained that for higher temperatures, the tensile strength decreases and for lower temperatures, the tensile strength of the adhesive increases. Another factor that varies with temperature is the material properties, as at higher temperatures the adhesives begin to soften while at lower temperatures they become brittle. It is notable that this remains the same for all adhesives subject to testing. Because of the tensile strength variance with respect to temperature, it is difficult to maintain any maximum strength value for a large range of temperatures. Because of this, extensive research must be performed on the strength behavior of adhesives for a low to high temperature range similar to active service exposure temperatures. Adhesive strength is quite closely related to the glass transition temperature, which in turn is dependent upon the temperature at which said adhesive is cured at. The glass transition temperature is also directly related to the overall composite repair time and when cured at a high initial temperature a shorter repair time is required, however, this often results in drastic void formation within the composite joint and therefore negatively impacting the overall strength of the joint. A solution to this has been proposed by Sanchez Cebrain, in which he proposes utilizing isothermal stages in a two step curing process. The proposed process decreases the overall repair time from four hours to just thirty minutes as well as decreasing void formation. As mentioned earlier, with decreased void formation comes increased mechanical performance. This process is especially useful as many composite bonded repairs are performed ‘in field’ at where the curing temperature needs to be low to avoid the auto-ignition temperature of the airplane fuel. To conclude, adhesives ideal for bonded repairs are such that they can be cured at low temperature, stored at ambient temperature, and have a short cycle time.

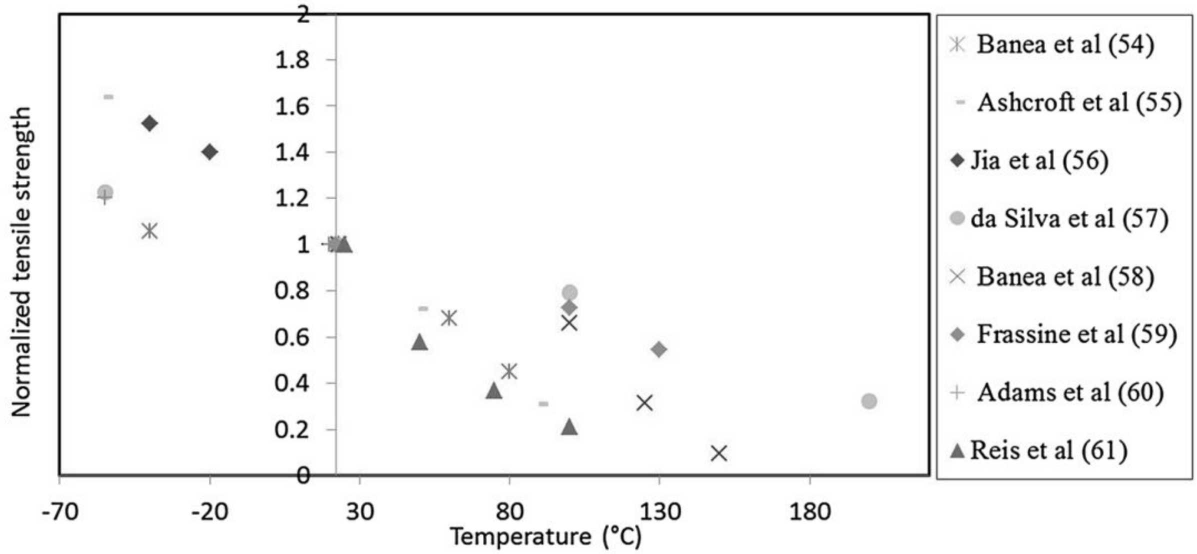

Fig. 6 Temperature dependent tensile strength properties of structural adhesives, test results from Refs. [54–61]

Next, the effect of temperature on composite materials will be discussed. A similar study was conducted regarding composite materials and the behavior of their mechanical properties with varying temperatures. Again, mirroring the results from the adhesive/temperature study, the overall tensile strength tends to decrease with an increasing temperature while increasing with a decreasing temperature. In particular, the study applies to the mechanical properties of glass fiber reinforced polymer samples. Probable causes for this occur when the glass transition temperature is approached and result in a softening of the resin matrix. A resin matrix softening causes the interfaces between matrices and fibers to weaken, however for advanced post-curing in fiber reinforced polymer composites, approaching the glass transition temperature increases viability. On the contrary, where resin matrix softening causes a decrease in tensile strength, at low temperatures the increased tensile strength is a result of the fiber reinforced polymer matrix embrittlement and hardening, however this is dependant upon the type of polymer matrix and the relevant sub-zero properties. A study performed by Di Ludovico found a substitute for the usual resin matrix, replacing it with a higher glass transition temperature epoxy which improved failure rates for lower glass transition temperatures. A separate study conducted by Takeda found reversed mechanical behaviors for a thin graphite/epoxy cross-ply composite laminate that increased tensile strength with increasing temperature. The study also found that thicker laminates performed similarly to the previous results where tensile strength decreased with temperature. Because of this revolutionary research, when applying bonded repair joints the thickness of the patch being applied requires careful consideration. The difference in the thermal expansion coefficients of the polymer matrix and fibers is the factor that makes fiber reinforced polymer composites sensitive to temperature variations. Though at lower temperatures the tensile strength can be seen to increase, it is suspected those same lower temperatures combined with the contraction differences while the fibers and matrix are cooling increase the fiber/matrix interface stresses which then result in micro-cracking. A similar process is suspected at greater temperatures instead due to the differences in thermal expansion between the fibers and matrix. The change in the composite's operating and curing temperatures represents the product of all remaining stresses. Studies show that elevated temperature exposure produce a decrease in both the flexural and shear strength present in the fiber/matrix interface.

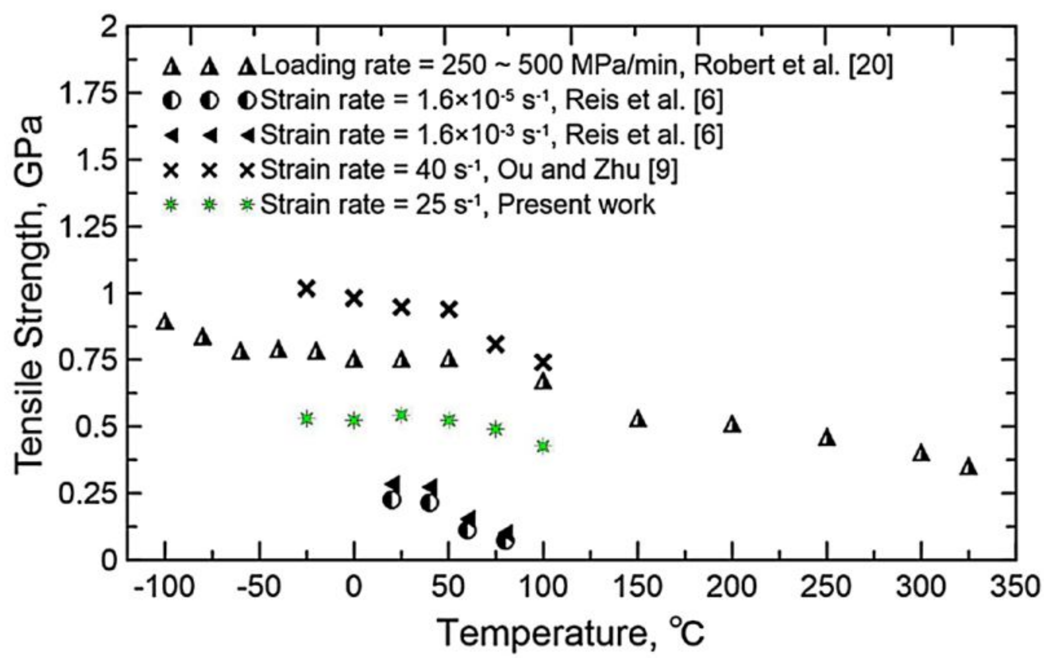

Fig. 8 Tensile strength of FRP composite coupon with respect to different temperature [74]

The final material discussed in reference to temperature variations is the adhesive joints mechanical behaviors. The coefficients of thermal expansion of the adhesive joint are directly related to its strength. It can be concluded from the research of many scientists that in general, with lower temperatures tensile strength increases while with higher temperatures the strength value declines, as similar to adhesives and composite materials. The temperature range for the study was conducted between -35 and 60 degrees celsius and concluded that the maximum tensile strength for the glass fiber reinforced polymer laminates and an epoxy adhesive, was achieved at 40 degrees celsius. Once temperatures exceeded the glass transition temperature of the adhesive, the total strength and stiffness were reduced. Therefore, picking an adhesive composite patch pair material with a relatively higher glass transition temperature would result in better performance. Another study by Sousa, concluded that ultimate load and stiffness decreased by 18% and 22% for an elastic polymer glass fiber reinforced polymer joint after undergoing 150 thermal cycles. Once 150 thermal cycles was surpassed, the overall performance reduction was minimal. A common trait used to verify and foresee the mechanical performance of composite bonded joints for various temperatures is fracture toughness. Fracture toughness has been found to perform opposite of conventional strength, where it increases with increasing temperature and decreases with lower temperatures (only up to the glass transition temperature), however this only applies to mode I tensile loading. Possible explanations for this result include heat induced matrix ductility, also once the temperature surpasses the glass transition temperature it causes a decrease in the fracture toughness due to adhesion loss. Mode II testing provides completely different data and no common trend is obvious providing inconclusive data on the subject. Because only a small number of results from mode I and mode II testing are available, there is no conclusive answer regarding fracture toughness and its variance with temperature.

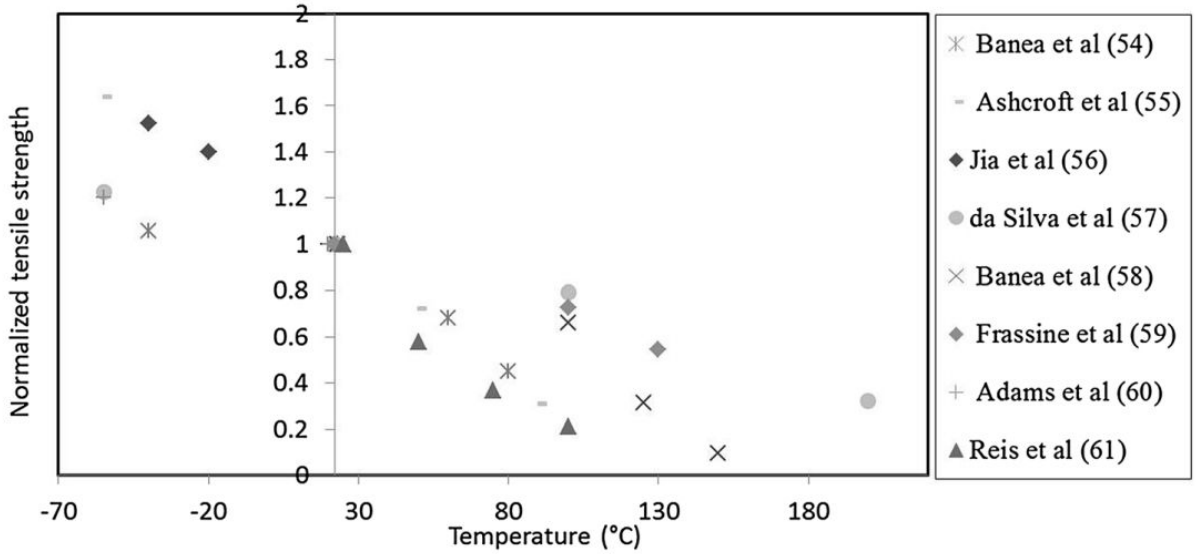

Fig. 6 Temperature dependent tensile strength properties of structural adhesives, test results from Refs. [54–61]

The next section will cover moisture, its absorption by adhesives, as well as the effects moisture absorption has on mechanical behaviors. For a given bonded assemblies structure, the resins and adhesive tend to absorb a higher moisture content than any other individual component such as the composite laminate, matrix, or interface. Different adhesives have different saturation capacities with variable rates of absorption depending on the exposure time and condition, and humidity and temperature level. Because there are so many different factors, it is difficult to obtain clear data for each individual adhesive and so in order to maintain a safety factor acceptable to design, the moisture attack is assumed to be the worst possible. Moisture content has the ability to change the properties of the adhesive by plasticization, swelling, cracking, and hydrolysis. Whether or not moisture content has affected an adhesive can be observed through given adhesive's sorption and desorption cycles, where a change in the adhesives properties can be determined by the saturation limit and resorption rate increase. Once an adhesive has absorbed enough moisture to make it highly saturated, even utilizing high temperature drying it is often difficult to remove all traces of that moisture without causing external damage in the form of blistering. All of the above factors culminate to impact adhesive choice for a composite bonded joint, and so knowledge of the desorption, resorption, and the saturation limit are necessary.

Again, as similar to the temperature effect and presented in figure 11, the overall tensile strength of the adhesive tends to decrease with respect to increasing temperature. Researchers due this diminishing strength is due to possible chemical degradation, stress induced from swelling, and plasticization. An important trait to note is that unless a void is created, lower percentage moisture contents within the adhesive can be ignored if the moisture can be sure to get absorbed acting curing takes place. Therefore when choosing an adhesive for use in a bonded joint it is paramount to obtain its information regarding its moisture absorption properties and mechanical behavior in response to moisture content.

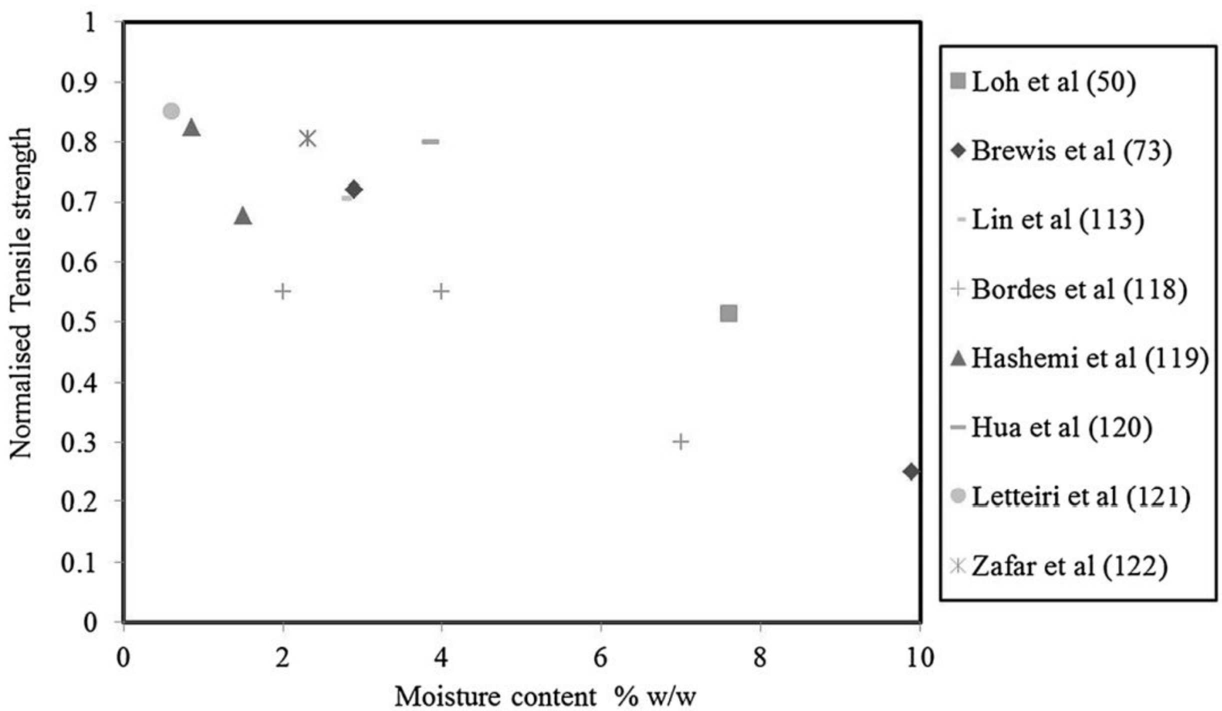

Fig. 11 Normalised tensile strength at various levels of moisture uptake [50, 73, 113, 118–122]

Subsequently, the paper addresses moisture content's effects on composite materials. Composite moisture intake is characterized by the polymer matrix, matrix-fiber interface, and an almost irrelevant value by the fiber itself. Most moisture absorption occurs through diffusion, while capillary and percolating flow account for the rest with the final two being dependent upon the presence of damage. The damage dependent factors automatically increase the rate at which moisture is absorbed as well as the saturation limit. Because moisture absorption is dictated by the matrix and fiber properties, moisture absorption properties differ by material. As with the reabsorption precedents for adhesives, the moisture absorption rate and diffusivity of a composite increases with its subsequent reabsorption cycles. This happens because as moisture invades the composite’s polymer network, it overcrowds the network causing swelling where micro-cracking is a result of the swelling. Moisture content in composite materials is more serious than in adhesives as it can sometimes result in irreversible modifications to the structure of the polymer itself through a moisture particle induced chemical degradation, debonding, or cracking. Because irreversible changes are a possibility, research such as the reversibility of the wet/dry cycle of a composite and thus reversing the damage done by moisture content, are important in the application of repair bonded joints. Much research has been done to verify the degradation of ultimate material strength when exposed to moisture in fiber reinforced polymer composites. In particular, Akay studied the effects of moisture absorption on the internal adhesion strength for the fibre-matrix of fiber reinforced polymer and found that the moisture weakened the level of adhesion connecting the two. Because the effect of moisture on composite strength has been well documented, for the sake of durability the composite material, studies recommend pre-bond drying techniques to prevent moisture diffusion during repairs.

The next section reviews the effects of moisture on adhesive joints. For bonded joints there are two separate categories detailing the moisture effects; pre-bond moisture and post-bond moisture. Pre-bond moisture entails the moisture absorbed by individual components within the composite structure such as pre-bond adhesive and composite laminate while post-bond applies to moisture absorption present after the bonding takes place.

Pre-bond moisture has been found to have a very clear impact on the mechanical performance of composite bonded joints and so it is imperative to be able to determine the sources of this moisture. Pre-bond moisture can be introduced in a number of ways among them: during manufacturing processes, carbon fiber reinforced polymer treatment processes, storage, environmental exposure, etc. Though the impact of pre-bond moisture is clear, there is still a noticeable lack of research on the effect it has on mechanical properties. The studies that are published all seem to agree that moisture content negatively impacts strength, in support research performed by Parker discovered reduced strength for single lap-shear joints. More research found that higher concentrations of pre-bond moisture resulted in higher incidents of void formation, however void formation can be halted by thoroughly drying, curing in at equal pressures, and using a textured adhesive film. Moisture content percentages of 0.5% and under do not seem to significantly affect composite bonded joint strength, however more research is necessary to be able to determine this for certain. Though very small moisture content percentages do not seem to produce structural integrities, as soon as the moisture content percentage approaches 1.3% the strength can be seen to decrease and once it surpasses 1.3%, the strength decline becomes much more intense. Because the strength decline is essentially negligible for small moisture contents, the typical moisture content percentage for composites in service is around 0.8%.

Sources of post-bond moisture are often dependent upon the environmental service variations including but not limited to humidity, temperature, wind, and exposure time. Similar to pre-bond moisture, studies found that increased levels of post-bond moisture correlated with a degradation of bonded joint strength where the rate of strength degradation is dependent on the amount of exposure and type of exposure and the effects on the specific bonded joint materials. A fascinating study performed by Jeoung, provided data supporting the increase in failure strength by as much as 21% for a composite bonded joint with a moisture content percentage equal to 1%. The study also showed that once the 1% moisture content percentage was surpassed, the failure strength began to follow the trend and suffer serious degradation. This is an important study because it shows that complete drying, though in practice currently, is not the optimal parameter for maximum failure strength in the composite bonded joint. It can be reasoned that this increase in strength is due to the prevention of delamination in the composite bonded joint. Currently it's impractical to attempt to achieve this 1% moisture content as only a slight increase would cause irreparable damage, because full strength recovery in the bonded joint cannot be attained without further damage to the material. Because of the variability of composite bonded joint materials and how they behave when subjected to moisture, complete performance data for the materials in use should be on hand prior to material selection.

When temperature and moisture both impact a bonded joint the combination of the two effects is called the hygrothermal effect and is more severe than either of the two's independent effects. For the most part, when exposed to increased temperatures, the moisture sensitivity of the material is more severe. Figure 13 displays this effect for the same material under similar conditions with temperature being the variable and shows that the material at higher temperature absorbs more moisture. A study conducted by Mijovic and Weinstein provided data supporting the irreversible effects produced by the hygrothermal effect. Their research showed that instead of behaving reversibly, the moisture content effects when applied at elevated temperatures become irreversible. The combination of elevated temperatures and moisture content produced chemical degradation within the composite bonded joint's matrix and interface. Because of this research it can be determined that the mechanical properties of both composite materials and adhesives are impacted when subject to the hygrothermal effect. For the composite material, the greater the hygrothermal effect the greater the decrease in strength, and for adhesives the greater the hygrothermal effect causes the glass transition temperature to decrease which in turn lowers the active service temperature. Though the hygrothermal effects on material properties are well known, the hygrothermal effect on service life and durability of composite bonded joints is still misunderstood due to lack of relevant research.

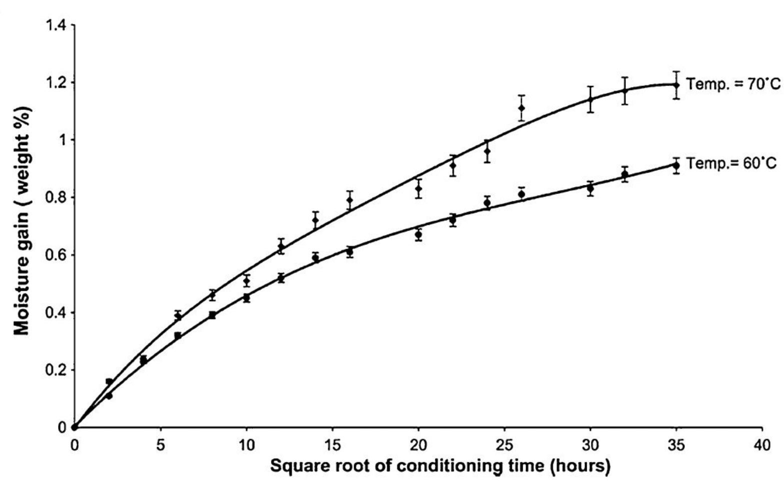

Fig. 13 Moisture absorption kinetics of carbon/epoxy composites at 60 °C temperature and 95% RH, and at 70 °C temperature and 95% RH [52]

Analysis of Bonded Joint Repairs:

Because of the complex structures present within composite bonded joints, evaluating them is quite difficult. The added effects of moisture and temperature only serve to make evaluation of the structures more complicated. Because of the intense complexity of these systems, finite element analysis is among the more popular methods for determining the optimal parameters for the maximum joint performance. Finite element analysis is preferred over traditional experiments as it provides a much cheaper and quicker alternative. Figure 14 shows the optimal parameters for a scarf repair joint and stepped lap repair determined using finite element analysis

Another method used that is more popular for its ability to include temperature and moisture factors is the cohesive zone modeling method. The cohesive zone modeling method excels for analysis in humid environmental conditions while relying upon the traction-separation law. Distinct to this method, because moisture concentration negatively affects the cohesive properties, in order to properly predict failure behavior the moisture dependent cohesive properties are required.

The final method discussed is the open-faced method and though has not been thoroughly vetted, provides a promising option to reduce the cost and time required as opposed to traditional long term fracture durability testing. This method will allow for the prediction of long term durability, which is a subject of much scrutiny. Using a combination of cohesive zone modeling and open-face testing, the secret to durability for bonded joints under considerable environmental stress is starting to be uncovered.

In Conclusion:

Because new and advanced composite materials continue to be discovered every year, the mechanical behavior of these advanced composites under environmental conditions needs to be evaluated in order to take advantage of the improved material properties. Continued research in these fields will lead to improved repair time, costs, and effectiveness. Because there is no generalized trend for all composites, adhesives, or bonded joints, the effects of temperature, moisture, and hygrothermal must be studied in depth in order to gain understanding of each with the end goal being to continually improve the composite bonded repair technology. Current composite repair methods can already be improved by implementing the vacuum-curing method (as opposed to the standard autoclave method). The vacuum-curing method provides increased mobility without sacrificing quality, as this method can be performed at in-field locations, and therefore shortening the overall repair time which saves money. Another improvement currently being researched for its ability to improve current repair times is self healing materials. More studies should also be conducted into the realm of hygrothermal effects on composite bonded joints, as this will start to provide an understanding of long term bonded joint durability.