Università degli Studi di Bologna

Scuola di ingegneria ed architettura

Corso di Laurea in Ingegneria Meccanica

JOINING ADHESIVE TECHNOLOGY FOR COMPOSITE SANDWICHES

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1. Memoria

A lo largo de este proyecto hablaremos sobre la tecnología de los adhesivos, donde veremos los distintos factores que influyen y que deben tenerse en cuenta a la hora de diseñar una unión adhesiva. También veremos las distintas tensiones a las que pueden estar sometidos los adhesivos, la resistencia que presentan ante ellos, así como los distintos tipos de uniones que podremos encontrarnos.

Para finalizar veremos las estructuras tipo sandwich, centrándonos en aquellas con núcleo de nido de abeja, donde veremos los distinto elementos que componen estas estructuras, los esfuerzos a los que pueden estar sometidos y los distintos tipos de fallos que pueden generarse.

1.1.- INTRODUCCIÓN

Las uniones adhesivas en materiales compuestos en su proceso en el cual se aplica un adhesivo entre las superficies de dos materiales (substratos), que permanecerán una vez que el adhesivo se haya secado.

Los fenómenos que tienen lugar en este tipo de proceso son:

- Adhesión: es el estado o fenómeno por el cual dos superficies o materiales distintos se unen por la acción de fuerzas de absorción y atracción
- Cohesión: es la fuerza de atracción entre partículas adyacentes que las mantiene unidas dentro de una misma sustancia.

La máxima adhesión se obtiene cuando el adhesivo y el sustrato están en contacto íntimo, es decir, cuando el adhesivo es capaz de penetrar totalmente en las rugosidades y mojar toda la superficie. Por lo tanto, el fenómeno de adhesión depende principalmente de:

-La energía superficial del sustrato: energía necesaria para romper los enlaces intermoleculares dando lugar a una superficie. En el caso de los líquidos, esta energía tiene el mismo valor que su tensión superficial.

Cuando tenemos un sustrato con energía superficial superior a la tensión superficial del adhesivo, las moléculas del líquido son atraídas hacia la superficie del sólido, debido a las fuerzas adhesivas que se produce entre ambos materiales. Este hace que el líquido se vaya expandiendo a lo largo de la superficie del sustrato favoreciendo la humectación del mismo.

-Ángulo de contacto: ángulo que forma una gota del adhesivo con la superficie del sustrato, y cuyo tamaño permite determinar el grado de mojabilidad del líquido sobre el sólido, así como ciertas características superficiales (como por ejemplo la energía superficial del sustrato). Consideramos que el adhesivo moja al sustrato si el ángulo de contacto mide menos de 90º.

-Estado superficial: la presencia de sustancias extrañas puede reducir la energía superficial de los materiales a unir, y por este motivo, normalmente, es necesario realizar tratamientos de limpieza superficial que permitan eliminar dichos residuos.

En resumen, para el mismo adhesivo, cuanto mayor sea la energía superficial de los sustratos, menor será el ángulo de contacto, y por lo tanto, se obtendrá un mayor mojado.

1.2.- TIPOS DE FALLOS EN UNIONES ADHESIVAS

La resistencia de una unión adhesiva depende, en primer lugar, de la unión entre sustrato y adhesivo (adhesión) y de las fuerzas internas del propio adhesivo (cohesión).

Los posibles fallos en una unión adhesiva son los siguientes:

- Fallo por cohesión, cuando se produce la ruptura del adhesivo.

- Fallo por adhesión, cuando la separación tiene lugar en la interfaz adhesivo-sustrato.

- Ruptura del sustrato, cuando es el sustrato el que rompe antes que el adhesivo o que la interfase sustrato-adhesivo.

En ocasiones, puede producirse un fallo adhesivo y cohesivo al mismo tiempo.

1.3.- CARGAS Y SOLICITACIONES

Los esfuerzos que pueden producir las roturas vistas anteriormente son:

a) Cargas de compresión: son generados por fuerzas perpendiculares al plano de unión que producen una reducción de volumen y un acortamiento del cuerpo en la dirección en la que son aplicadas. Las cargas de compresión producen una distribución de las tensiones a los largo de la línea de unión muy uniforme, es decir, todas las aéreas de la línea de unión soportan la misma carga.

b) Cargas de tracción: se producen por fuerzas que actúan perpendicularmente a la línea de unión, tendiendo a alargar la probeta. Los esfuerzos de tracción se consideran aceptables siempre que la carga aplicada no esté concentrada en algún punto de la superficie, ya que esto produce la aparición de momentos flectores, que llevan a la generación de esfuerzos de pelado, y por tanto, a una distribución no uniforme de las tensiones.

c) Esfuerzos de cortadura: se producen por la aplicación de fuerzas exteriores paralelas a la línea de unión. Estos esfuerzos se distribuyen sobre la línea de unión de manera que las mayores tensiones se localizan en ambos extremos. Los adhesivos presentan muy buena resistencia ante este tipo de esfuerzos.

d) Esfuerzos de pelado: se producen cuando uno de los sustratos es más flexible que el otro. Al aplicar una tensión elevada de tracción sobre uno de los extremos de la línea de unión se generara un momento flector que somete al adhesivo a una tensión de pelado. La acción de esta tensión afecta a una línea muy delgada en el borde de la unión.

e) Esfuerzos de desgarro: ocurren de forma similar que los de pelado, solo que en este caso el sustrato no se deforma. Al aplicar un esfuerzo de tracción, un extremo de la junta se verá afectado mientras que el resto permanece apenas sin tensión.

f) Esfuerzos transitorios: Son debidos a un incremento único del esfuerzo hasta una carga máxima. Normalmente no aparecen en la práctica, pero son de gran importancia a la hora de determinar la resistencia nominal de los adhesivos.

g) Esfuerzos estáticos o permanentes: Cuando se aplican esfuerzos constantes que se prolongan a lo largo del tiempo bajo una determinada temperatura se genera un desplazamiento relativo, débil pero constante, de los elementos de la unión sin ser necesario un aumento de la fuerza aplicada. Este desplazamiento seguirá progresando hasta que se produzca el fallo de la estructura. Este fenómeno recibe el nombre de fluencia.

h) Esfuerzos dinámicos: Podemos distinguir dos tipos de ciclos de solicitación dinámica; Regulares (vibraciones): Se trata de esfuerzos que se repiten periódicamente .En este tipo de situaciones el adhesivo tiene que absorber la energía de deformación lo cual puede provocar un agrietamiento progresivo que culmine con la fractura del material. Este fenómeno se denomina fatiga.

i) Irregulares (impactos): Estas cargas producen un impacto que genera una onda de compresión que se transmite por las diferentes partes de la unión adhesiva. Las consecuencias de este tipo de esfuerzo dependen de la capacidad de absorción de energía del sustrato y del adhesivo.

j) Tensiones residuales: Cuando tenemos un adhesivo que cura a una temperatura superior a la ambiente, pueden producirse tensiones internas adicionales debidas a las deformaciones térmicas originadas por los diferentes coeficientes de dilatación de los substratos y del adhesivo.

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1.4.- DISEÑO DE LA UNIÓN

El diseño de la unión adhesiva es considerado el factor más importante para obtener las máximas prestaciones del adhesivo.

Por lo tanto, estas uniones deben ser diseñadas de manera que:

- El adhesivo trabaje sometido principalmente a esfuerzos de cortadura.
- Se reduzca la aparición de esfuerzos de pelado y cortadura.
- Se proporcione una buena distribución de las tensiones a lo largo de toda la línea de unión.

Podemos encontrar distintos tipos de uniones adhesivas, pero probablemente los más comunes son los que se exponen a continuación.

1.4.1.- Uniones a tope

Este tipo de uniones presenta una buena resistencia ante esfuerzos de tracción y compresión. Sin embargo, si la carga es aplicada perpendicularmente al eje axial se pueden producir momentos flectores que provoquen el desgarro de la unión.

Estas uniones se pueden mejorar mediante una serie de técnicas que permitan aumentar el área de contacto incrementando a su vez la resistencia al desgarro:

- Biselando la unión
- -Mediante el empleo de cubrejuntas.

1.4.2.- Uniones a tope

Las uniones solapadas son las más empleadas debido a su facilidad de montaje y a que permite unir materiales de espesores pequeños, además presentan una gran resistencia frente a cargas axiales, ya que solicitan la unión a cortadura Como regla general, no se aconsejan longitudes de solapamiento superiores a 25-30mm, ya que no se consigue un aumento de la resistencia de unión.

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Aun así, estas uniones también sufren concentraciones de tensión provocadas por la desalineación de las cargas, produciendo momentos flectores sobre los sustratos que dan lugar a efectos de desgarro.

Para aumentar la resistencia de las uniones a solape, contamos con una serie de métodos que introduces variaciones en el diseño tanto en las zonas de unión como en los espesores de los sustratos:

- Diseñar la unión de manera que los esfuerzos estén alineados
- Rigidizar los sustratos, para evitar la aparición de esfuerzos de desgarro.
- Flexibilizar los bordes de los sustratos en la zona de unión, mediante un biselado de los bordes, para que se adapten mejor y se reduzcan los esfuerzos de pelado.

1.4.3.- Uniones en T y en esquina

Este tipo de uniones presentan muy baja resistencia ante esfuerzos transversales ya que generan esfuerzo de desgarro y de pelado. Dentro de las fuerzas normales, los esfuerzos de compresión son más peligrosos que los de tracción, ya que pueden producir el pandeo de la chapa y la aparición de momentos flectores sobre ella.

Para mejorar la resistencia de este tipo de uniones se recurre al empleo de escuadras y elementos de diseño que aumenten el área de unión, así como la rigidez, con el objetivo de evitar los esfuerzos de flexión.

Además del tipo de unión existen otros aspectos que debemos tener en cuenta a la hora de diseñar una unión adhesiva, entre los que destacamos:

- El espesor
- El tipo de adhesivo
- Los tratamientos superficiales necesarios

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1.4.4.- Influencia del Espesor

La distribución y el tamaño del espesor del espesor a lo largo de la línea de unión son un factor muy importante en el diseño de una unión adhesiva.

La utilización de un adhesivo no uniforme generará elevados esfuerzos de pelado, reducirá la fuerza de adhesión, favoreciendo el fallo de la estructura, y empeorara la transmisión de los esfuerzos a través del seno del adhesivo.

En cuanto al tamaño, un espesor excesivamente grande aumenta el riego de aparición de burbujas o huecos que sirven como concentradores de tensión favoreciendo la rotura del material. Mientras que espesores muy pequeños pueden perjudicar la unión al no llegar a cubrir todos los huecos u ondulaciones superficiales de los sustratos generando zonas propensas a la separación.

Para evitar estas situaciones contamos con una serie de métodos que nos permiten controlar el espesor de la línea de unión:

- Esferas de cristal
- Fibras de cristal
- Microfibras
- Separadores mecánicos

1.4.5.- Tipos de adhesivos

Hoy en día, podemos encontrar muchos adhesivos en el mercado, los cuales podemos clasificar en función de sus propiedades físicas o del tipo de mezcla:
En función de sus propiedades físicas:

-Adhesivos rígidos: Proporcionan uniones de gran rigidez, y a pesar de mostrar bajas resistencias en aplicaciones dinámicas o frente a esfuerzos de pelado, existen formulaciones más tenaces de todos ellos que les permiten mejorar su respuesta ante estas situaciones.

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-Adhesivos tenaces: Presentan excelentes rendimientos tanto en aplicaciones dinámicas como cuando las cargas aplicadas generan esfuerzo de pelado y/o desgarro.

Adhesivos flexibles: La función principal de este tipo de adhesivos es la de sellado. Sin embargo, también son utilizados en uniones estructurales ampliando la superficie de aplicación para aumentar la rigidez del ensamblaje.

En función del tipo de mezcla:

-Adhesivos bicomponentes mezclados: Dentro de esta categoría encontramos aquellos adhesivos que requieren de una mezcla previa antes de ser aplicados sobre la superficie del sustrato. Una vez mezclados los dos componentes, el adhesivo presenta una vida útil limitada.

-Adhesivos bicomponentes no mezclados: Sobre una de las superficies del sustrato se aplica el adhesivo y sobre la otra, aunque en una cantidad más pequeña, un activador. El adhesivo se cura por la reacción de dos componentes al juntar ambas superficies. Como se puede observar no se requiere de una mezcla previa para el curado del adhesivo.

-Adhesivos monocomponentes: En este grupo no se requiere de mezcla alguna y el adhesivo es el único componente aplicado sobre la superficie de los sustratos.

1.4.5.1.- Adhesivos rígidos:

- Anaeróbicos: bicomponentes no mezclados
- Cianoacrilatos: monocomponentes
- Epoxis: bicomponentes mezclados o monocomponentes

1.4.5.2.- Adhesivos tenaces:

- Acrílicos: bicomponentes no mezclados

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1.4.5.3.- Adhesivos flexibles:

- Siliconas: monocomponentes
- Poliuretanos: bicomponentes mezclados o monocomponentes

1.4.6.- Tratamientos superficiales

En ocasiones es necesario realizar tratamientos superficiales para limpiar o mejorar la energía superficial de los sustratos. Podemos distinguir:

-Tratamientos superficiales pasivos: son aquellos que no modifican químicamente la superficie. Ejemplos de este tipo de procesos son: desengrasado en fase de vapor, tratamiento en baños de ultra sonidos y abrasión mecánica.

-Tratamientos activos: a diferencia de los anteriores, si modifican la estructura química de la superficie del sustrato, entre ellos destacamos: tratamiento con plasma, anodización, grabado, descarga en corona y tratamiento de llama.

1.5.- ESTRUCTURAS TIPO SÁNDWICH

Las estructuras tipo sándwich son un tipo de estructuras de materiales compuestos constituidas por dos finas y resistentes láminas (pieles), entre las que se coloca un núcleo grueso y ligero. Ambos materiales se pueden unir entre sí por medio de un adhesivo.
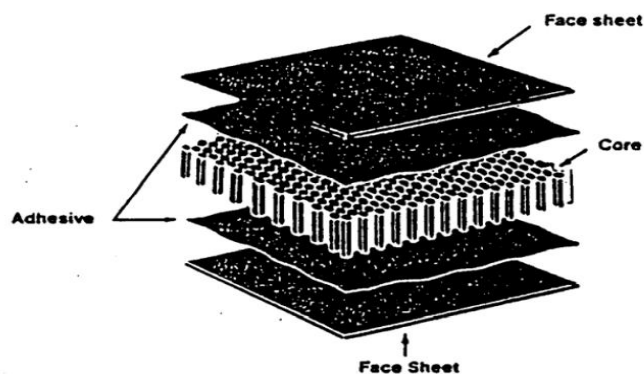
Figure 1.1.-   Esquema de una estructura tipo sandwich

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Este tipo de diseño permite obtener estructuras de gran rigidez y de bajo peso, con una alta resistencia a la flexión.

Esta resistencia, como podemos observar en la tabla que se muestra a continuación, puede aumentarse incrementado el espesor del núcleo. Debido a la ligereza de los materiales con los que está fabricado el núcleo, un mayor espesor no supondrá un gran aumento del peso del conjunto.
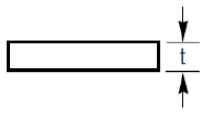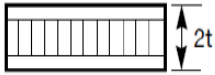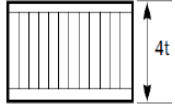
	Sólido	Material Compuesto Tipo Sándwich.	Material Compuesto Tipo Sándwich.
	t	$2t$	$4t$
Rigidez Relativa	100	700 7 veces más rígido	3700 37 más rígido
Resistencia	100	350 3.5 más fuerte	925 9.25 más fuerte
Peso Relativo	100	103 3% de aumento del peso	106 6% de aumento del peso

Figure 1.2.-   Influencia del espesor del núcleo

Sin embargo, el espesor de cada uno de los elementos que constituyen este tipo de estructuras, debe estar dentro de unos ciertos límites:
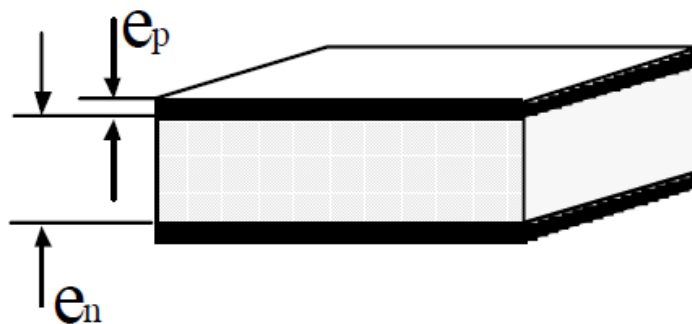
Figure 1.3.-   Espesores en una estructura tipo sandwich

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$$10 \leq \frac{e_n}{e_p} \leq 100$$

$$0{,}25\text{mm} \leq e_p \leq 12{,}7\text{mm}$$

$$0{,}025\text{mm} \leq e_a \leq 0{,}2\text{mm}$$

$$20 \frac{Kg}{m^3} \leq \gamma_n \leq 1000 \frac{Kg}{m^3}$$

Donde:

e_p : Espesor de la piel

e_n : Espesor del núcleo

e_a : Espesor del adhesivo

γ_n : Densidad del núcleo

1.5.1.-Tipos de estructuras tipo sándwich

En función de la distribución del núcleo podemos encontrar diferentes estructuras tipo sándwich, de las cuales, la más utilizada suele ser la honeycomb.
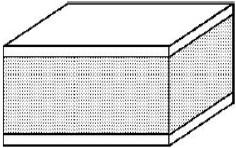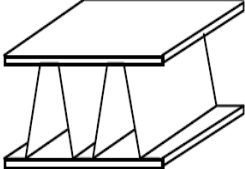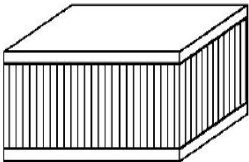
	Núcleo Expandido
	Núcleo Nervado
	Honeycomb

Figure 1.4.-   Clasificación en función del tipo de núcleo

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1.6.- HONEYCOMB

Las estructuras honeycomb o nido de abeja se caracterizan por poseer un núcleo similar a la geometría de un panal, lo cual minimiza la cantidad de material utilizado.

1.6.1.- Nucleo

Existen distintos tipos de núcleo nido de abeja dependiendo de la geometría que presenten las celdas que lo constituyen, siendo la más utilizada la hexagonal.

hexagonal	rectangular	seta
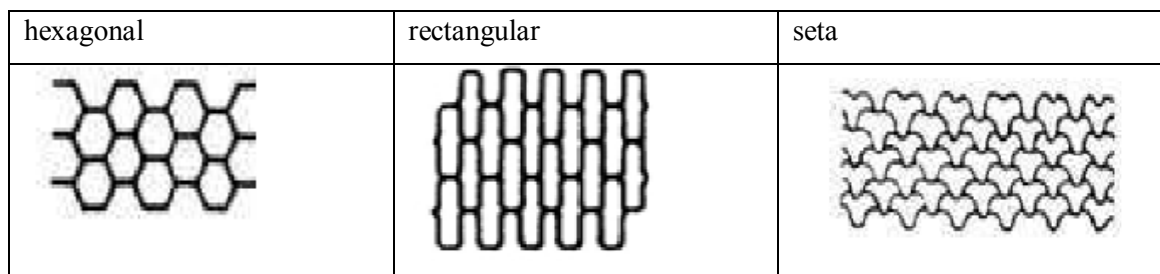
Figure 1.5.-   Geometrías más comunes de un núcleo de nido de abeja

Estas celdas pueden ser fabricadas con distintos materiales en función de las aplicaciones que se van a realizar. En situaciones donde se requieran estructuras de gran rigidez se utilizaran materiales metálicos, aceros inoxidables y aleaciones de aluminio en su mayoría, mientras que si se requieren estructuras de gran ligereza y menor rigidez se emplearán materiales no metálicos como fibras arámidas, termoplásticos y fibra de carbono, entre otros.

1.6.2.- Revestimientos (pieles)

Las pieles o revestimientos son materiales compuestos laminados, formados por la unión de una resina, que constituye la matriz, y un material más resistente (fibras entrelazadas en dos direcciones).

En este tipo de materiales compuestos las fibras soportan las cargas mientras que la principal función de la matriz es mantenerlas unidas y protegerlas.

1.6.3.- Adhesivos

Dependiendo del procedimiento utilizado para fabricar el sándwich se puede utilizar una película de adhesivo o no. Si los revestimientos se curan y luego son unidos al núcleo, es necesario utilizar una capa de adhesivo entre cada capa y el núcleo. Sin embargo, si el honeycomb se fabrica mediante un co-curado del revestimiento y el núcleo, no es necesario el uso de un adhesivo, puesto que las resinas de las láminas de fibra pueden actuar como medio de unión entre los dos elementos.

1.6.4.- Comportamiento mecánico

Cuando se aplica una carga a este tipo de estructuras, cada uno de los elemento cumple una función determinada. Las pieles resisten las cargas en el plano y los momentos flectores, proporcionando casi toda la rigidez a flexión ya que tienen un modulo de elasticidad superior al del núcleo y están situadas a una mayor distancia del eje neutro de la estructura. El núcleo proporciona la distancia necesaria entre las pieles, aumentando la rigidez a flexión, y soporta los esfuerzos de cortadura, los cuales transmite a las caras como una flexión alrededor del eje neutro de la estructura. Además, suministra a rigidez a cizalla y estabilizan las cargas, evitando que los revestimientos pandeen.
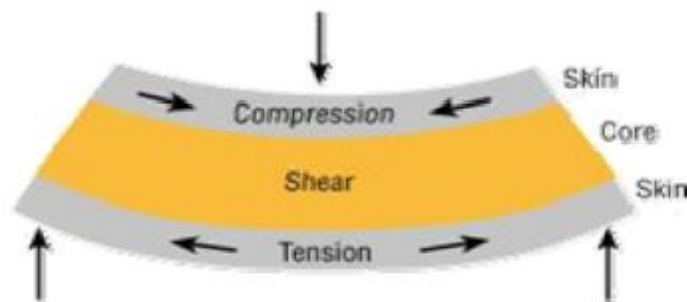
Figure 1.6.-   Distribución de las cargas en una estructura tipo sandwich

1.7.-   MODOS DE FALLO DE UNA ESTRUCTURA SÁNDWICH

En el caso de las estructuras tipo sándwich podemos encontrar tres tipos de fallos, los cuales se pueden clasificar en función de donde se originen, pudiendo aparecer de forma independiente o combinada. Se puede diferencia entre:

- Resistencia insuficiente
- Inestabilidades locales
- Inestabilidades globales

1.7.1.- Resistencia insuficiente

Dentro de este grupo encontramos los fallos producidos en las pieles y en el núcleo. Tienen lugar cuando se superan los valores de resistencia última del material.

a) Fallo de las pieles:
- Rotura por tensión plana
- Rotura por cortadura interlaminar

b) Fallo del núcleo:

c)Fallo por cortadura transversal
- Cortadura del núcleo
- Despegue de la unión núcleo-piel
- Aplastamiento del núcleo
- Tensión o compresión plana en zonas de rampa

1.7.2.- Inestabilidades locales

Uno de los elementos, una o ambas caras, el núcleo o la unión fallan por separado.

1.7.3.- Inestabilidades globales

Suponen un fallo generalizado del pan

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2. Introduction

Throughout history, we can find numerous examples in which the human being has used the adhesives for the development of various activities; the Egyptians used this technology to link the leaves of the papyrus, the Babylonians used bituminous cement for building statues...

Since the eighteenth century, with the Industrial Revolution, to the present, the composite materials have become very important. Its development has been driven mainly by its good resistance to high loads, durability and for allowing to join materials of different nature.

Today, the adhesive bonds have multiple engineering applications that are becoming an ideal choice in the automotive, aerospace and shipbuilding sectors, increasing their use against mechanical joints, thanks to the advantages offered, among which we highlight:

- Uniform tension distribution
- Ability to thermal and electrical insulation
- Less manufacturing cost
- Absence of corrosion problems
- Elimination of welds
- Possibility of joining materials of different nature
- Less structural weight

The continued development of this technology will get mechanisms with better mechanical properties that today offer us.

3. Adhesive bonds

The adhesive bonds in composite materials, are a process in which an adhesive is applied between the surfaces of the material or materials, both being joined after the adhesive has cured.

In this kind of structures we can distinguish two parts:

- The Adhesive: substance that we applied between the surfaces of materials to get a union.
- The Substrates: The materials we want to unite through the adhesive.
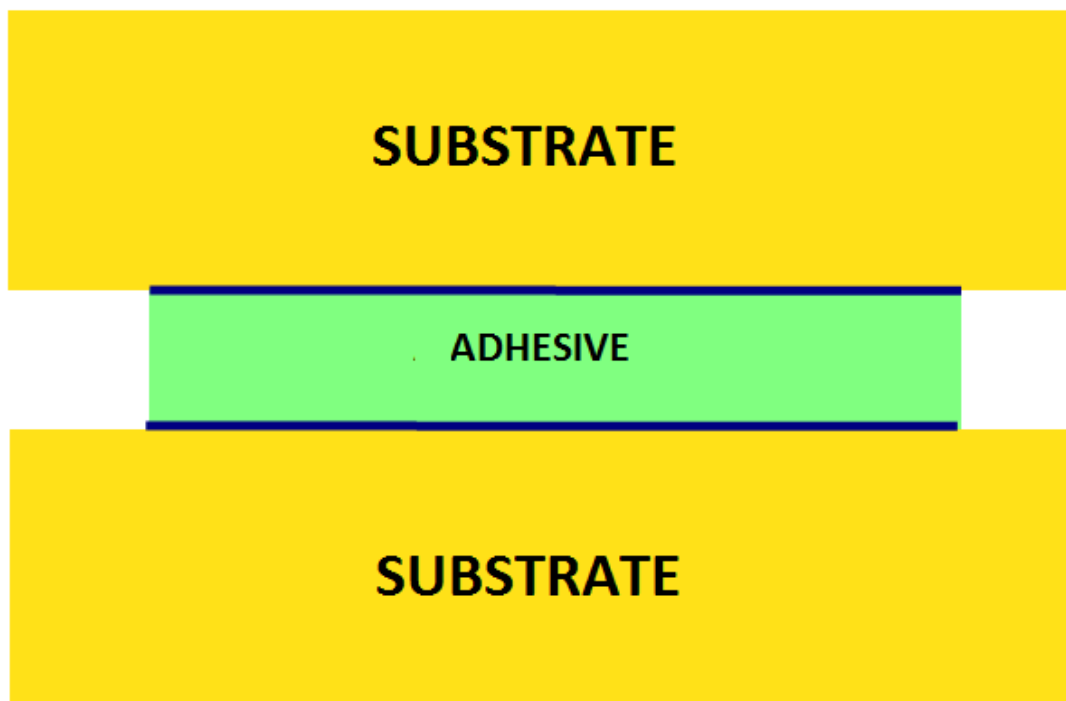
Figure 3.1.- Basic scheme of an adhesive bond.

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3.1.- ADHESION AND COHESION

Adhesion is the state or phenomenon whereby two surfaces or different materials are joined by the action of forces of attraction and absorption. The maximum adhesion is obtained when the adhesive and the substrate are in intimate contact, that is, when the adhesive is able to fully penetrate the roughness and wet all surfaces.

As can be seen, the adhesion phenomenon depends mainly on the intermolecular contact (wetting) and the surface state of the substrate. For a given surface tension of the adhesive, wetting depends on the surface energy of the substrate (the higher surface energy the better wettability). Obviously, a contaminated or low energy surface will reduce the bond strength, so cleaning treatments are usually necessary.

Cohesion, however, is the force of attraction between adjacent particles which hold them together in the same substance. This force includes strong interatomic bonds of the polymeric chains and weak (Van Der Waals forces) of attraction between different chains.

Therefore, in all adhesive bonding, it is expected that maximum resistance is generated by the cohesive forces within the adhesive.
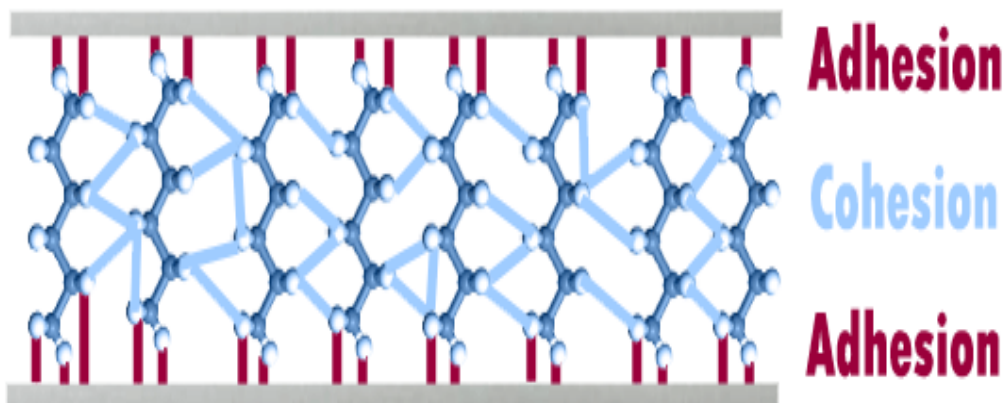
Figure 3.2.-   Phenomena of adhesion and cohesion in an adhesive bond.

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3.2.- ADHESION THEORIES[1]

There are several theories to explain the phenomena of adhesion. This is because some theories can be applied to some cases but not others. At this point we will expose the different theories that explain this binding mechanism:

3.2.1.- Mechanical theory

According to this theory, the union is due to the anchoring of the adhesive in the pores and roughness surface of substrate. During the process, the adhesive will be filling the surface cavities of the substrat. When it hardens, both substrates are joined together. Therefore, the roughness and porosity are important factors in the adhesion process. Sometimes surface treatments are needed to improve the surface conditions of the substrates. It is necessary to ensure good wettability of the substrate by the adhesive, because the non-covered cavities can be areas of bond failure.

3.2.2.- Diffusion theory

This theory is used to explain the adhesion between polymers. The adhesion would have place due to the interdiffusion of the molecules on the surface planes, leading to the creation of an area of adhesive-substrate transition. Within this mechanism we find the self-adhesion, adhesion of compatible polymers and the thermoplastic or solvent welding .

3.2.3.- Electrical theory

According to this theory, adhesion occurs due to electrostatic forces produced by the existence of an electrical double layer that forms when two materials of different nature are contacted. This theory can only be applied to very specific cases.

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[1] To this point we have used concepts used by Madrid Vega M. (2000) in Tecnología de la adhesión.

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3.2.4.- Adsorption theory

It defends the idea that adherence occurs as a result of contact between two materials and surface forces generated at the interface. These forces have the name of secondary forces or Van Der Waals force.

The process in which the adhesive and substrate are contacted is called wetting. When the surface tension of the adhesive is less than the surface energy of the solid, this is capable of wetting the substrate surface with a lower contact angle of 90º.

4. Joint design

The joint design is considered the most important factor to achieve the maximum performance of the adhesive chosen. To do this, the adhesive bonds should be designed so that the adhesive works mainly subjected to shear stresses. The normal stresses, tension and compression, may be acceptable, but any deviation in the line of application may cause the presence of bending moments, subjecting the adhesive to unfavorable stresses of peel and tear.

In general, to achieve a good performance the set must be designed based on general principles and taking into account a number of general factors:

- Most of the paste area should contribute to the bond strength.
- The Design must comply the limits of application of the adhesive (depth of curing, gap filling, shelf life, etc.)
- The Union should be designed so that the adhesive works in the direction of maximum strength and reduce stress concentrations
- The glued area should be as large as possible, within certain limits. An excessive increase of the area can reduce the resistance of the union.
- The adhesive must be able to transmit the expected loads
- The physical and chemical properties of the adhesive must be compatible with the substrate
- The fatigue strength of the adhesive as well as its ability to absorb energy must be previously known.

4.1.- LOADS AND STRESSES[2]

In practice, the most common failures are due to the ignorance of the efforts that will support the adhesive bond during the service. Therefore, it is essential to know the extent and nature of the stresses which will be submitted the set before deciding the adhesive type that we will use.

The mechanical loads that will be applied on the assemblies will generate tensile, compression, shear, peel and tear efforts, being the last two the most unfavorable for this type of structures. We can also find certain situations where tensions generated by the appearance of secondary phenomena with temperature changes can occur.

Normally, these tensions are not shown individually, but usually are presented combined with each other.

Schematically, the solicitations to which the adhesive bonds will be subjected can be:

4.1.1.- Compression

Compressive stresses are generated by perpendicular forces to the joint plane, producing a volume reduction and a shortening of the body in the direction in which they are applied. Compression loads produce a very uniform stress distribution along the bond line, all the areas of the bond line endure the same load. The incident forces ratio and joint area are calculated to calculate their tensions.

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[2] *To this point we have used concepts used by Josefa Conesa Guillén in Evaluación mecánica de uniones adhesivas de materiales compuestos en la construcción naval.*

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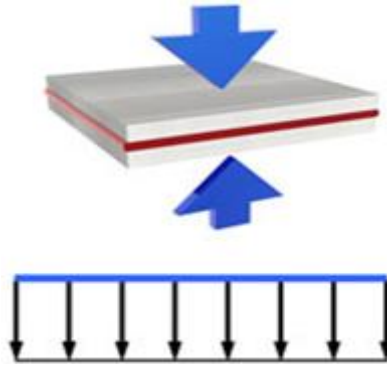
Figure 4.1.-   Compressive stress and its distribution on the bond line.

4.1.2.- Traction

These stresses are caused by forces acting perpendicular to the bond line, tending to elongate the test piece. Tensile stresses are acceptable if the applied forces are uniformly distributed throughout the section. However, if the applied load is concentrated at one point of the surface can be dangerous, since the occurrence of bending moments, leading to the generation of peeling efforts, and therefore to a nonuniform distribution of tensions.
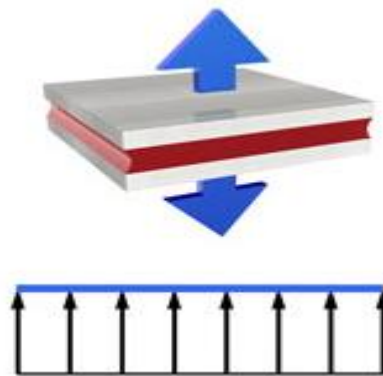
Figure 4.2.-   Tensile stress and its distribution on the bond line.

4.1.3.- Shear, peel and tear

Normally there aren't many applications in which the adhesive bonds are subject to tensile and compression, being most common in practice to find shear, peeling and tearing loads.

The shear stresses are produced by the application of external parallel forces to the connecting line.

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Peeling efforts are very dangerous in the adhesive bonds and occur when one substrate is more flexible than the other. By applying a high tensile stress on one end of the bond line a bending moment is generated, which subjects the adhesive to a peeling stress. The action of this stress affects a very thin line at the edge of the union, while in the rest of the joint tension isn't almost detected.
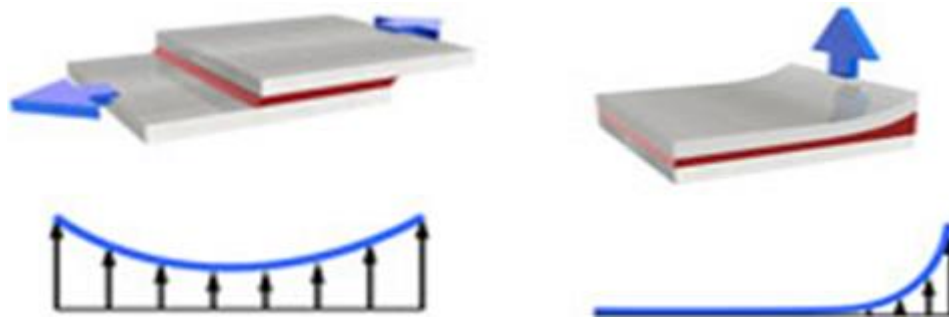
Figure 4.3.-   Shear stress and peel stress, and its distributions on the bond line.

Tear efforts occur in a similar way to peeling. By applying a tensile stress, one end of the board will be affected while the rest remains almost without tension. The difference with the peeling is that in this case the substrate is not deformed.
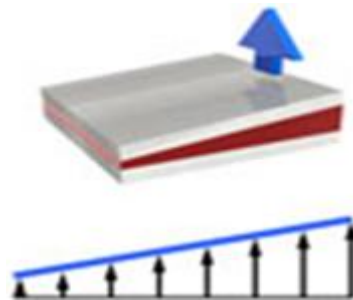
Figure 4.4.-   Tear stress and its distribution on the bond line.

The application of this type of stresses produces a less uniform and more difficult to calculate distribution.

The shear stresses are distributed over the bond line producing stress concentrations at both ends, while in peeling and tear efforts most of the stress is concentrated at only one end.

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4.1.4.- Transient efforts

These efforts are due to a unique increase of the effort to the maximum load. Although they don't typically appear in practice, these efforts are important in determining the nominal strengths of adhesives.

4.1.5.- Static or permanent efforts

These are constant efforts over a period of time.

If a stress acts in one direction for an extended period of time, it generates a relative displacement, weak but constant, of the binding elements without requiring an increase in the applied force. This movement will continue progressing until the failure of the structure occurs.

This phenomenon is called fluency and essentially depends on temperature.
Because of this, in the inside of the adhesive bond the strength of cohesion will be reduced gradually until it reaches a moment in which the molecules begin to slide over each other. This will produce a plastic deformation difficult to appreciate if the measure devices are not available.

The fluency phenomenon could be reduced to acceptable limits with an appropriate design or even eliminated if we correctly choose the adhesives.

4.1.6.- Dynamic efforts

There are two types of dynamic solicitation cycles:

- Regular (vibratory)
- Irregular (impacts)

When we have a regular alternative effort the adhesive has to absorb the deformation energy. This can cause a progressive cracking that result in the fracture of the material. This phenomenon is called fatigue.

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In the case of having repetitive efforts regularly accompanied by abrupt cycles, the calculation of the adhesive bond is complicated. This is because the evolution of the efforts is not known exactly and the reaction of the adhesive will depend on these sudden changes. In such situations, comparative trials must be done in which we take into account the application expected or the resistance calculations based on known values of the permanent resistance (by applying safety factors that allows us to get closer to the real situation).

In the study of any adhesive bond subjected to dynamic stresses it is essential to know the fatigue resistance properties of the adhesive.

For irregular efforts, apart from possible deformations suffered by the substrates, the impact generates a compression wave transmitted by the different parts of the adhesive bond depending on the energy absorption capacity of the substrate. Therefore, the consequences on a particular union, subjected to these efforts, are directly dependent on the nature of the materials composing the substrates.

This way, when designing an adhesive bond where irregular efforts are going to be applied, we must take into account the impact absorption capacity of both, the substrate and the adhesive. Since in the case of having a substrate that poorly absorbs the impacts, the vibrations produced will be transmitted to the adhesive, which should present a good absorption of energy capacity to avoid the failure of the structure, and vice versa.

4.1.7.- Residual stresses

When we have an adhesive bond in which the adhesive is cured at a temperature above the ambient, additional internal stresses can be generated (residual stresses) caused by thermal deformations. These deformations are caused by differences in the expansion coefficients of both materials (adhesive and substrate).

These residual stresses are difficult to calculate analytically, therefore, photoelastic methods are used for their study.

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The use of a more flexible adhesive, the use of a greater thickness of the adhesive layer, the use of a lower temperature and the use of a longer and slower time of cooling can end the problem.

Figure 4.5.-　　Internal tensions of an adhesive bond measured by photoelastic cells.

4.2.-　COMMON ADHESIVE JOINTS[3]

The ideal adhesive joint is when the adhesive is demanded in the direction of the greater stress concentration, reducing the presence of undesirable peeling and tearing efforts, and thus providing a good stress transmission and distribution along the whole system. This can be achieved with an appropriate design.

We can find various types of adhesive joints, but probably the most common ones are the following:

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[3] To this point we have used concepts used by Anaguano D.P. y Loachamin C.M.in Análisis de uniones por adhesión para materiales metálicos.
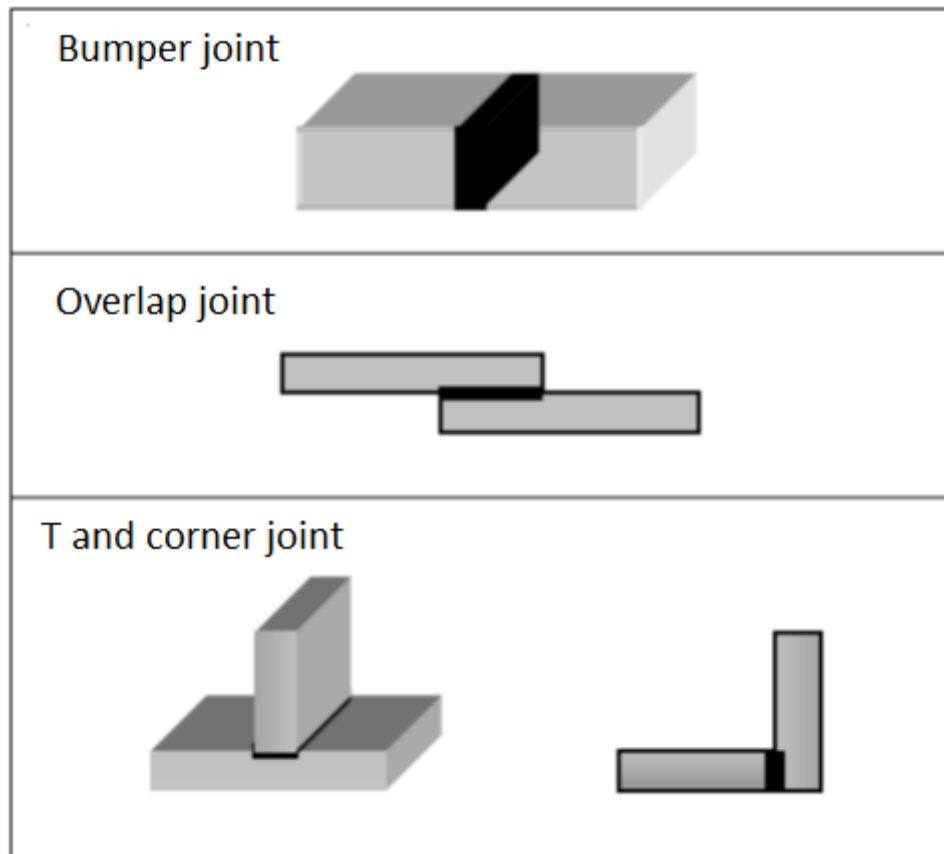
Figure 4.6.-   Typical adhesive joints.

4.2.1.- Bumper joints

This type of joint shows a good tensile and compression resistance. However, if the load is applied perpendicularly to the axis, bending moments that cause tearing of the union can be generated.

Bonding in this type of joints can be improved using complementary techniques that increase the contact area and in turn the tearing resistance:

- By bond bevelling
- By using joint covers

Due to design considerations, beveling is often used as a method to increase bond strength.

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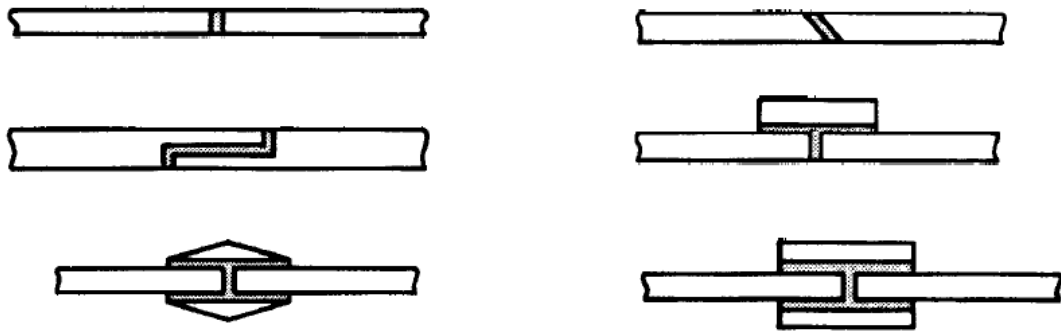
Figure 4.7.-   Adhesive bumper joints

In this type of joints, we can also find tubular bonding, they are currently used when the application requires axial and torsional loads. These joints may exhibit different designs due to the different geometry of the tubes.
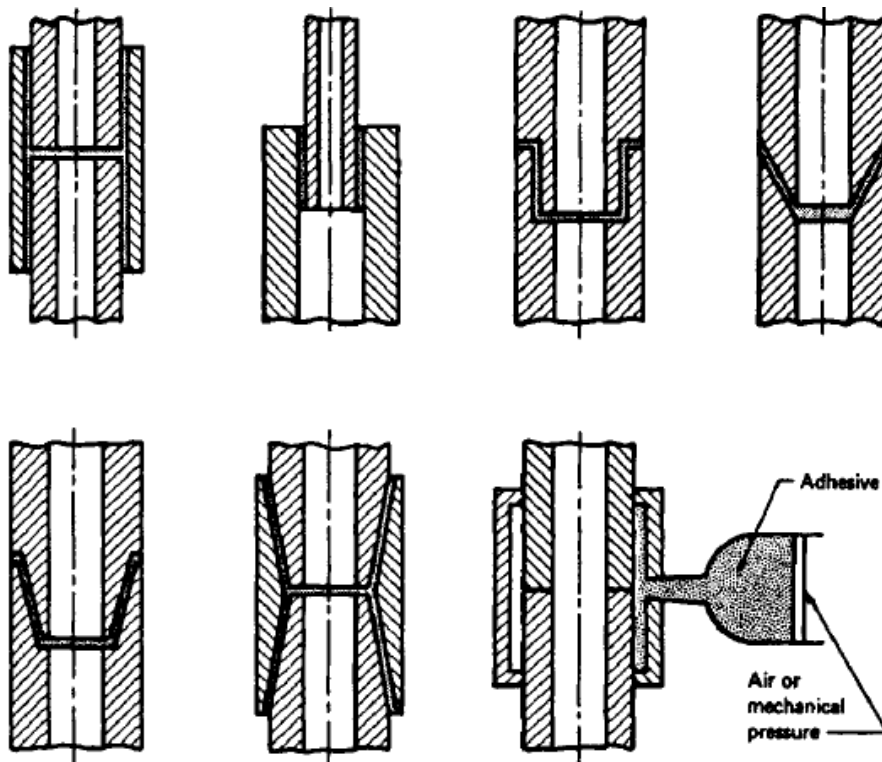
Figure 4.8.-   Tubular adhesive joints.

4.2.2.- Overlap adhesive joints

This is the type of joints more widely used due to their easy assemblage which allows the bonding of low thicknesses materials. Moreover, against axial loads, overlap joints demand

shear bonding, which is very convenient because, as above mentioned, the adhesive bonds show a great resistance to shear stresses. As a general recommendation, overlapping lengths should not exceed 25-30 mm

The shear resistance in this type of joints is directly proportional to the overlap width. However, due to the fact that the stresses concentrate at the end of the bonding line, the relationship between the overlap length and the shear resistance is not lineal, independently that an increase is observed.
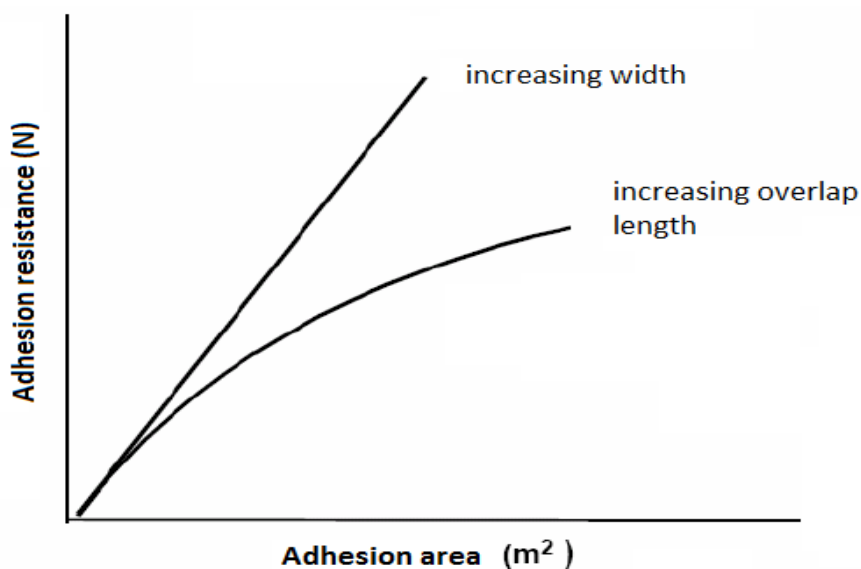
Figure 4.9.-   Resistance variation of an adhesive bond by increasing the width and length of overlap.

Still, these joints also support stress concentrations caused by loads misalignment, producing bending moments on the substrates that distort bonding and generate tearing.

There are a series of methods to increase overlap joints resistance, which introduce design variations in both, the bonding zones and the thicknesses of the substrates:

- Joint design with aligned stresses.
- Substrates stiffening, to avoid tearing stresses

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- Make flexible the edges of the substrates in the joining area for a better adapt and a reduction of peeling efforts. This can be achieved by a beveled edge.

As we saw above, the length and width of overlapping influence the bond strength, but they are not the only ones. The load from a substrate which exceeds its elastic limit depends on rigidity and thickness.
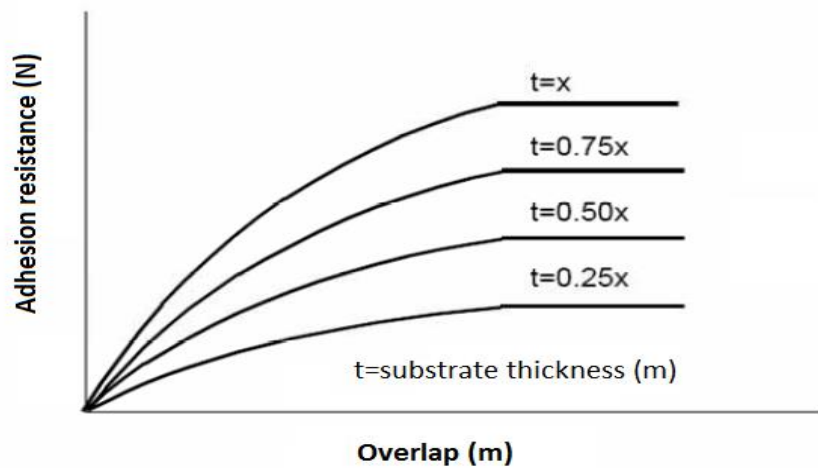
Figure 4.10.- Resistance variation of the adhesive bond against the overlapping of different thicknesses

Brunie and Houwink evaluated the relationship between thickness, overlapping and tension, and define as joint factor the ratio of the square root of the thickness between the overlap length.
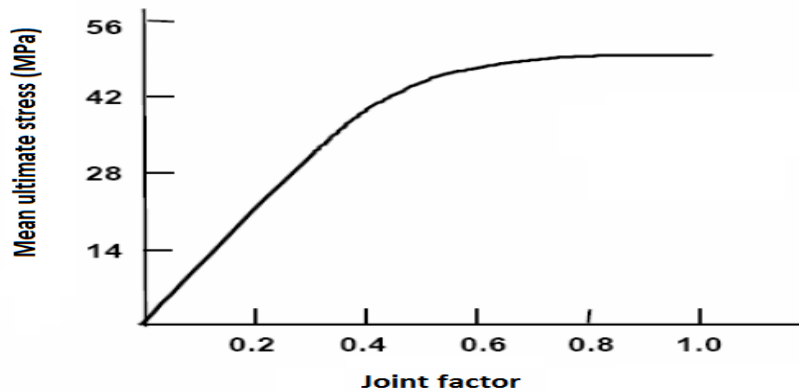
Figure 4.11.- Effect of the joint factor in the resistance of the adhesive bonds.

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Consequently, stiffening can be achieved by increasing the thickness of the substrate at the edges of the bonding zone, taking into account that the increase in the final weight should not be excessive.

Some of these possible solutions include:
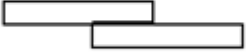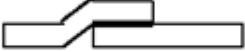
SIMPLE JOINTS	JOINTS REINFORCED
simple overlap joint	Double overlap joint
	Bevelling overlap joint
	Overlap joint
	Mechanized overlap joint

Figure 4.12.- Overlap adhesive joints

In some cases, due to design limitations, the joint is subjected to great tearing stresses, making the use of techniques which avoid the movement of the edges of the joint necessary. These techniques include: an increase of the stiffness or the area of the adhesive at the edge of the substrate, generating a wrinkle which favors a mechanical anchorage; or the development of a rivet or welding point on the edge.

4.2.3.- Adhesive joints in T

Joints in T show low resistance to transversal stresses because they generate tearing and peeling stresses. Compression stresses are more dangerous than bending ones, as they can produce the buckling of the sheet and the occurrence of bending moments on it.

Normally, to improve the strength of such unions, brackets and design elements that increase the bonding area and the stiffness are used, in order to avoid bending stresses.

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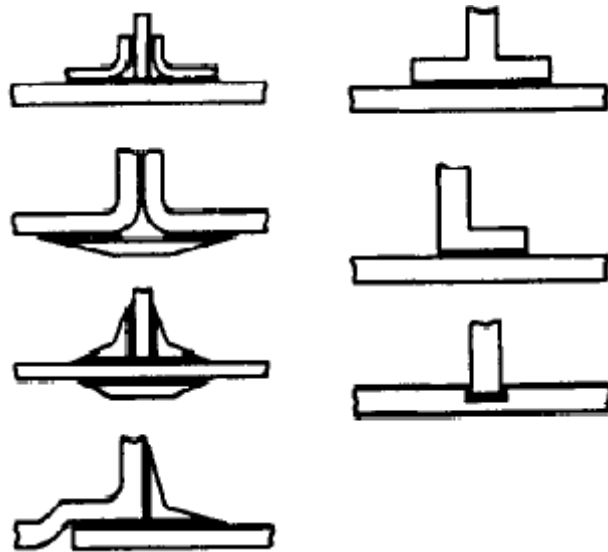
Figure 4.13.- Adhesive bonding in T.

4.2.4.- Adhesive joints in corner

Similarly to previous, this type of joints shows very low resistance to transversal and compression stresses.

The use of reinforcement elements (brackets or auxiliary parts fitted to) significantly improves the resistance of these joints.
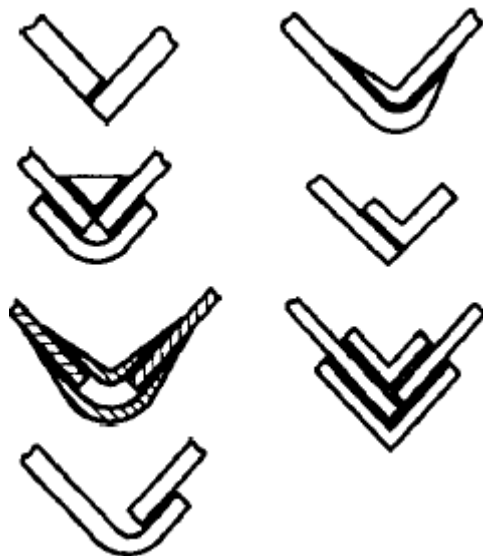
Figure 4.14.- Adhesive bonding in corner.

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4.3.- FRACTURE MODES IN ADHESIVE JOINTS

An adhesive joint resistance depends first, of the bonding between the substrate and the adhesive (adhesion) and the internal forces of the adhesive itself (cohesion).

The bonding resistance can be estimated by a break test. The possible failures in an adhesive joint are:

-   Cohesive failure, when the adhesive breaks.
-   Adhesive failure, when the separation occurs at the adhesive-substrate interface.
-   Substrate failure, when the substrate breaks before than the adhesive or the substrate-adhesive interface.
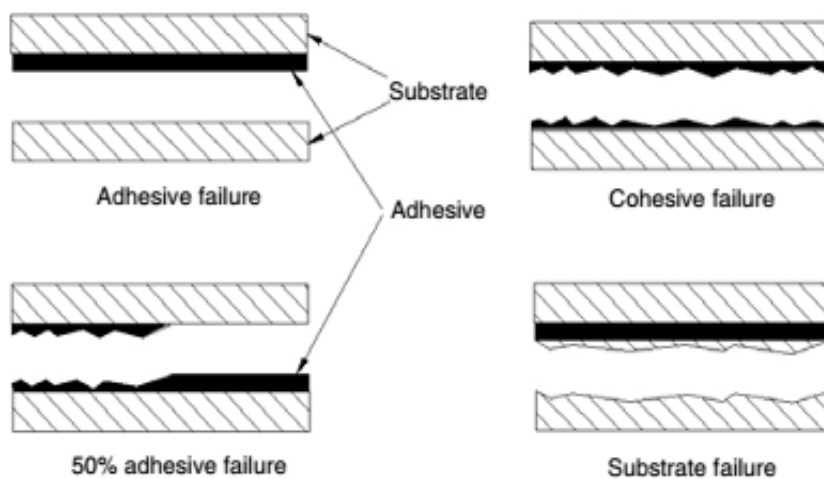
Figure 4.15.- Types of failures in the adhesive bonds.

When designing an adhesive joint, it is always intended to avoid an adhesive failure, or what is the same, to avoid interface failure.

The failure type of an adhesive bond is unpredictable, because the adhesion forces magnitude depends of a great number of factors difficult to completely control. However, the mechanical characteristics of the adhesive can be known and consequently, the cohesive failure loads under different stresses.

Substrate failure occurs due to the oversizing of the bonding zone. Therefore, it is considered a design flaw, because an amount of adhesive has been employed exceeding the necessary mechanical.

The adhesive joints failure can be produced by very different reasons, among them we can point:

- The presence of cracks or voids, as well as the development of residual stresses that can concentrate the stresses.
- The application of dynamic stresses that may favor the fatigue failure.
- Fluency.
- A bad compatibility between the adhesive and the substrate.
- A bad stresses transmission.
- A bad sizing of the whole system
- Application of normal stresses that may favor peeling or tearing in the adhesive.

5. Aspects to consider

To achieve a successful union we must take into account a number of parameters when making the design of the adhesive bond. Some of these factors to keep in mind are the following:

- The surface energy of both, the adhesive and the substrate to ensure a good adhesion.
- The curing characteristics of the adhesive.
- The size of the thickness of the bond line, so as to ensure a good transmission of the stresses.
- The effects that the adhesive bonds may be exposed to by the action of environmental agents, in particular by the presence of moisture in the environment.

5.1.- SURFACE ENERGY

The surface energy plays an important role in the interactions between the adhesive and the substrate to generate a good bonding.

The surface energy can be defined as the energy required to break the intermolecular bonds resulting in a surface. In the case of liquids, this surface energy has the same value as the surface tension, and it is due to all intermolecular forces acting in each molecule.

As shown in Figure 3.1, the molecules inside the liquid are subjected to cohesive forces which in average are zero. However, the molecules at the surface are not completely surrounded by other molecules, interacting more strongly with those in their vicinity. This creates a film with a certain tension, which makes difficult to move an object through the surface.

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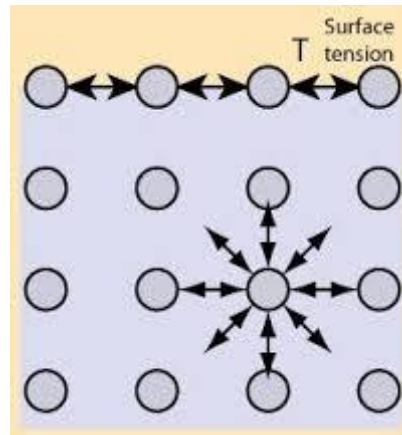
Figure 5.1.-   Basic diagram of the surface tension of a liquid

The substrates with a higher surface energy than the surface tension of the adhesive attract the molecules due to the adhesive forces between both materials. As a result of that, the adhesive expands along the substrate surface and wetting is favoured.

The presence of foreign substances (contaminants) may reduce the surface energy of the substrates, and it is why cleaning treatments become necessary.

If the substrates show surface energies substantially lower than the surface tension of the adhesive, surface treatments which improve the value of the surface energy can be applied, thus improving the wetting behaviour.

5.2.- CONTACT ANGLE

Another important factor when dealing with the surface wetting of a substrate is the contact angle. It can be defined as the angle which forms a drop of the adhesive with the surface of the substrate. Its value is indicative of the degree of wetting of the liquid to the solid (adhesive and substrate in our case) and also provides information about certain surface characteristics, such as the surface energy of the substrate.

The value of the contact angle mainly depends of the chemical interaction between the surfaces of the two materials. The adhesive will wet the substrate when the contact angle is below 90º.

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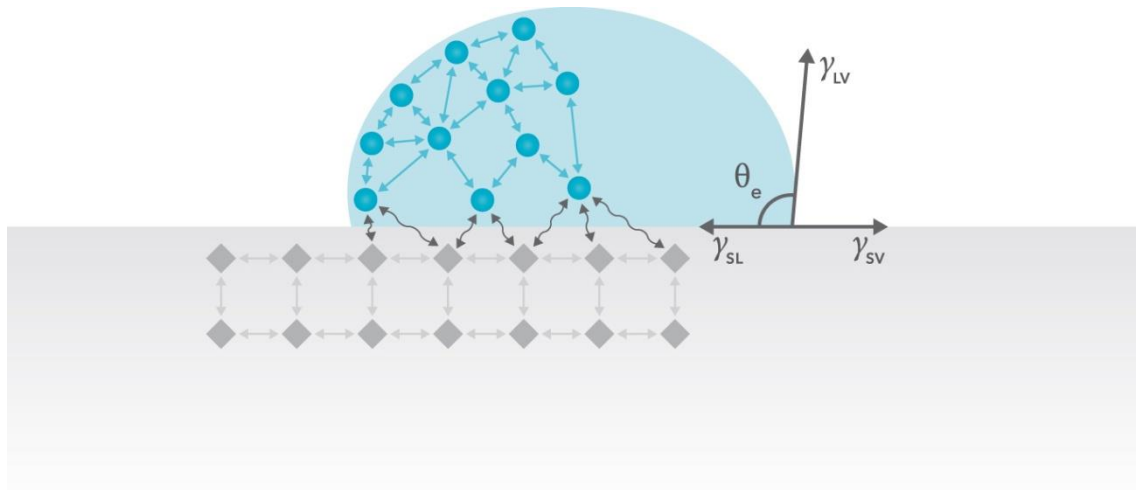
Figure 5.2.-   Contact angle between the surface of the adhesive and substrate

5.3.- THICKNESS

Another aspect to consider when designing an adhesive bond is the distribution and size of the thickness of the adhesive layer.

Thickness distribution along the bond line is a very important factor to obtain good adhesive properties .The use of a nonuniform adhesive generates a high peel stress and reduces the adhesion force, favoring the structure failure, and deteriorating the transmission of forces through the womb of the adhesive.

Normally, it is assumed that the thicker a layer is the greater its resistance will be. However, the application of a thick layer can lead to the generation of certain disadvantages, among which we highlight:

- Increased risk of generation of air bubbles or elements that may serve as stress concentrators, favoring the adhesive fracture
- Variation of curing properties producing internal tensions.
- Increased tensions at the ends of the adhesive.

However, excessively thin layers can prejudice the binding by not covering all the voids or superficial undulations of the substrates, generating areas prone to separation.

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To avoid these situations, we have a number of methods that allow us to control the thickness of the bond line. These systems should not produce voids in the adhesive that prejudice the binding of the set. Among them, we include:

- Glass spheres: The thickness of the conection band will have the size of the diameter of these mixed with the adhesive before application. The distribution of the spheres should be uniform and should not exceed 1% by mass of adhesive. An adhesive with a high percentage of spheres will produce an excessively rigid blend, while if the percentage is very small the thickness will lose uniformity along bondline.
- Glass fibers distributed along the adhesive
- Microfibers mixed with the adhesive
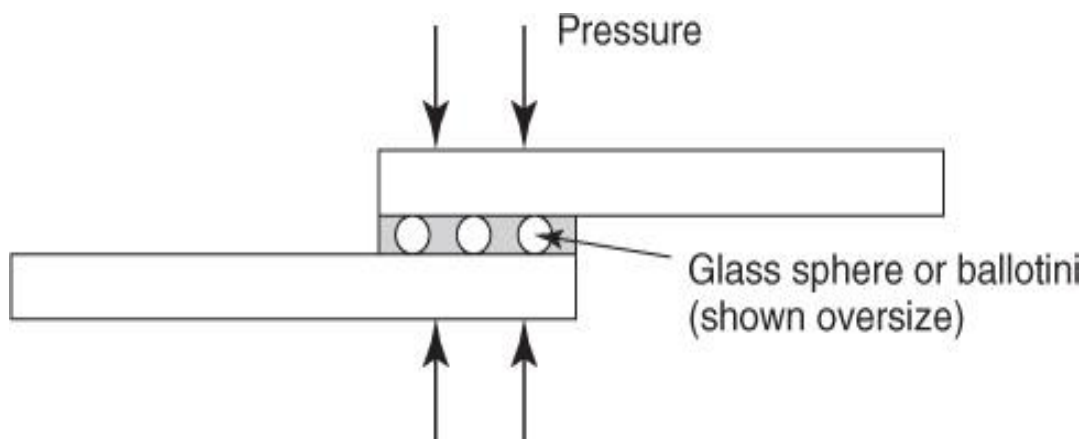
Figure 5.3.-   Control of adhesive thickness by the use of glass spheres.
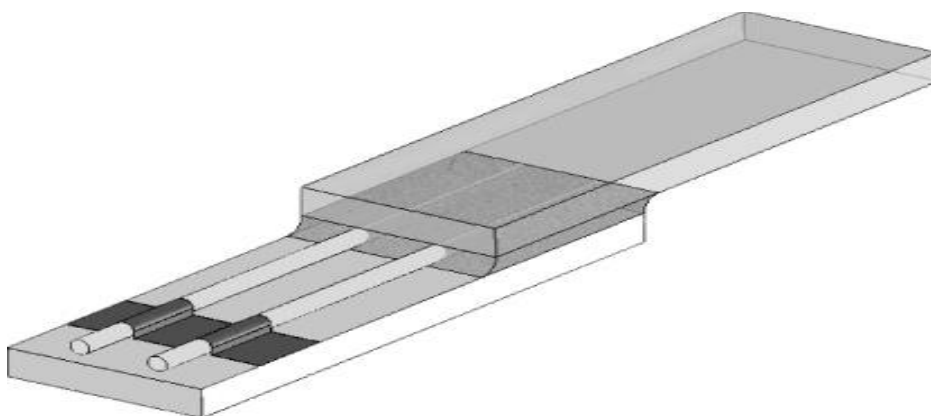
Figure 5.4.-   Control of adhesive thickness by the use of calibrated wires.

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As we discussed in previous chapters, due to the loads which may be subject these structures, stress concentrations can occur at the ends of the bond line. As shown in the figure, we can increase the stiffness in these areas by increasing its thickness.
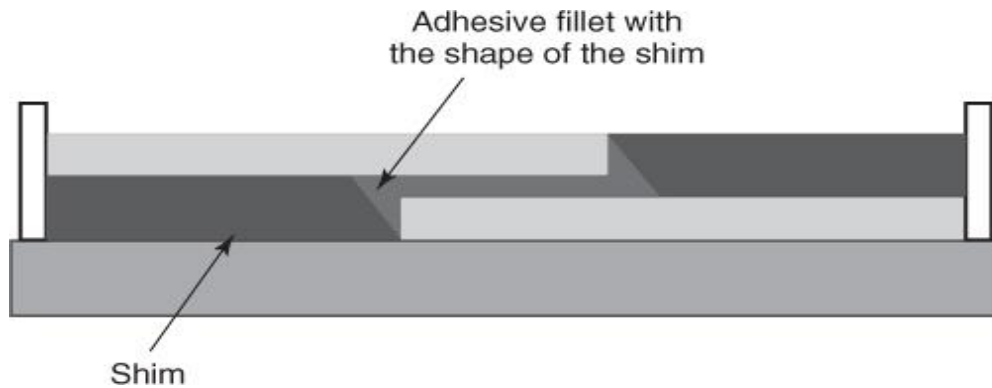
Figure 5.5.-   Control of adhesive thickness by the use of shims

Once the adhesive is dried, we should measure the resulting thickness to check that fits in our design. We highlight, among others, the following methods to obtain the thickness of the bond line:

- Measure the thickness of the whole with the help of a micrometer
- Directly measuring the thickness with the aid of a microscope

5.4.- CURED

The parameters influencing good curing of adhesive bonds are: pressure, curing time and temperature.

As we mentioned, the adhesion is a surface phenomenon that requires good wetting of the surface of the substrate by the adhesive. A good pressure during curing can improve wetting, helping the adhesive to reach voids and unevenness on the surface of substrates and providing greater control of the thickness of the bond line.

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With excessively long curing times it may happen that the adhesive dries before getting correctly and completely wet the substrate surface, resulting in future failures. If, however, we have excessively short times, there is a risk of leakage of the adhesive as well as a greater probability that voids are generated within it that can serve as stress concentrators triggering the breakage of the material

In the case of the temperature, if we have parts of the same material and thickness, all joints will be warmed at equivalent speeds. However, it is sometimes necessary to adjust the curing process to control the temperature cycles in which the parts to be joined have different masses or thermal conductivities, that is to say, the curing time for each assembly should be adjusted so that the adhesive mass in contact with the slower heating portion achieves proper curing.

Generally, in a process in which thick and thin parts are joined, or if the pieces have very different conductivities, the temperature reached by the adhesive in the thickest/lower conductivity piece can be much lower than that achieved by the adhesive in the thinner/higher conductivity piece. In extreme cases, the temperature may rise sufficiently to cause degradation of the adhesive or of the substrates.

Many adhesives cure at room temperature, which may involve excessively long curing times. This can be inconvenient, so in some situations heat is applied to accelerate the process. However, this process can generate different properties to those obtained with initial conditions. To reduce these variations, both situations should alternate; performing a first cure at ambient temperature followed by another at higher temperature.

Temperature and time are closely related. If the heating speed is too quick, the curing time will be too small, and vice versa, leading to the aforementioned faults.

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5.5.- EFFECT OF MOISTURE

Environmental factors can also directly affect the resistance of the adhesive bonds. Water is one of the agents that can impair the most the durability of the joints. Since most of the adhesive bonds are exposed to the action of water (liquid or gas), when the relative humidity reaches a value high enough it is impossible to avoid the diffusion into the adhesive. In this way, the adhesives susceptible to moisture become more sensitive when loads are acting on them.

At low concentrations moisture can act as a plasticizer which softens the adhesive. This effect produces a minimum impact resistance and can be reset with drying. However, as the concentration of water molecules begins to increase, irreversible changes that may affect the adhesion to the substrates and particularly to the interface between them may occur.

6. Types of adhesives[4]

We can find a lot of adhesives on the market today. In order to classify them, we can order them according to their physical properties or the type of mixture:

Depending on their physical properties:

- Rigid adhesives: junctions provide high rigidity, despite of low resistance in dynamic applications or peel efforts, there are more tenacious formulations for all that allow them to improve their response to these situations.
- Tenacious adhesives: They have excellent performance in both, dynamic applications and when applied loads generate peel stress and/or tearing.
- Flexible adhesives: The main function of these adhesives is sealing. However, they are also used in structural joints extending the application surface to increase the rigidity of the assembly.

Depending on the type of mixture:

- Bicomponent mixed adhesives: In this category are those adhesives that require a premix before being applied on the substrate surface. After mixing the two components, the adhesive has a limited lifetime.
- Bicomponent unmixed adhesives: On one surface of the substrate the adhesive is applied and over the other, although in a smaller amount, an activator. The adhesive cures by the reaction of two components joining both surfaces. As can be seen it does not require a premix for curing the adhesive.
- Monocomponent adhesives: In this group is not required any mixture and the adhesive is the only component applied to the surface of the substrates.

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[4] To make this classification, we are based on the realizated by Mario Madrid Vega in *Tecnología de la adhesion*,

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6.1.- RIGID ADHESIVES

6.1.1.- Anaerobics

Anaerobics are bicomponent unmixed adhesives which react in the absence of air or in the presence of metal ions. After the polymerization does not dissolve or melt with temperature or solvent.

These substances are perfect for applications in which the shear is the predominant effort. Generally they have low tensile strength so as to impact and peel.

This type of adhesive is suitable in metal assemblies where the presence of ions in the substrate surface promotes the polymerization process. When the surfaces of the substrates are passive (aluminum, nickel, zinc, gold, silver, etc.) using a chemical agent is required to cover the absence of ions. This agent is called activator. With non-metallic substrates (plastics, glass, wood, ceramic, etc.) applying an activator it is also required, but the use of these products with different substrates to metals is not recommended.

Obviously cure times are greater in the case of non-metallic substrates. These types of adhesives may also be cured by heat, achieving complete polymerization between 120°C and 150°C heating for about 30 min. Both corrosion and surface dirt impede the contact of the adhesive with ions preventing the polymerization reaction to take place.

Advantages of anaerobic adhesives:

-   Good chemical resistance
-   Excellent resistance to shear and compression
-   Fast curing times
-   Do not requires large surface finishes
-   Good temperature resistance (from -55°C to 149°C)
-   Good resistance to traction and metallic loads

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Disadvantages of anaerobic adhesives:

- Poor resistance to both tensile and peel
- Require the use of activators in the case of passive or non-metallic substrates.

These features make the anaerobic adhesives great for certain applications:
- Thread locking
- Flange sealing
- Retention of cylindrical parts
- Impregnation of metal pieces

6.1.2.- Cyanoacrylates

Cyanoacrylates are single component adhesives which cure rapidly in the presence of humidity when they are imprisoned in a thin film between two surfaces.

In most cases, the substrates have humidity absorbed from their surfaces. Thereby, when a drop of cyanoacrylate is compressed and extended between two surfaces, the thin film comes into contact with the moisture absorbed in the surface (basics), resulting in a rapid initiation of polymerization. The smaller the adhesive film is the lower the curing time will be.

Polymerization for this type of adhesives does not occur fastly when we have acidic surfaces or with large gaps, yet the fixing speed is typically fast enough for the application of some kind of activator.

Advantages of cyanoacrylate adhesives:

- Easy application
- Low curing times
- Good chemical resistance
- Produces colorless adhesions

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- Can be applied to different materials (metal, plastics, ceramics, wood, leather, glass, natural and synthetic rubber), and can also combine them.

Disadvantages of cyanoacrylate adhesives:

- Ability to looseness limited (usually 0.2mm)
- Low impact and peel resistance on metal substrates
- Low temperature resistance (maximum 80°C), but the most tenacious formulations can endure up to 120°C
- The blooming or blurring caused by the volatility of the monomer

These features make the anaerobic an ideal adhesive for certain applications:

- Automated assembly processes
- Glued of plastic parts (for example, the parts located in the passenger compartment of a car)
- In the electrical and electronics industry
- As curious applications we can emphasize its use in the unmasking of fingerprints by many police departments, as well as their use in the field of medical suture.

6.1.3.- Epoxies

This type of adhesives can be found in two versions: as bicomponent mixed adhesives and as mono component.

Two component epoxies have a good shelf life and require no refrigeration. This type of epoxies can be cured at room temperature but is generally necessary to apply high temperature to improve performance.

Furthermore, in the case of monocomponents its cooling is required and have a rather low useful life. Like the above, they require high curing temperatures.

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Epoxies are quite sensitive to the surface conditions of the substrates and the mixing ratio. So, usually, surface treatments are necessary before applying the adhesive.

These products are generally applied by hand, except in the case of large volume productions, where automatic dispensing equipment are used to accomplish the mixture before application onto the surface, with the aim of preventing human error in the mixture and the application.

Advantages of epoxies:

- Good filling characteristics in large volumes
- High resistance to shear and traction
- Good chemical resistance
- Good characteristics for of joining rigid surfaces
- Though is dielectric and thermal insulatior, can be modified to conduct both electricity and heat
- Resistance at temperatures up to 180ºC (may reach 250ºC in some formulations)
- Allows bonding substrates of various materials, even combined with each other

Disadvantages of epoxies:

- Troubles of absorption and diffusion of moisture within it
- Poor resistance to peel efforts and impact, which can be solved with more flexible formulations.
- Requires high curing temperatures
- High curing times
- Low life of mixture

Some areas of application of epoxies are:

- Aeronautical and electronic industry
- Construction industry (as additives for concrete and other construction elements)
- Production of composite materials

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6.2.- TENACIOUS ADHESIVES

6.2.1.- Acrylics

The acrylics are bicomponent unmixed adhesives in which isn't necessary a completely homogeneous mixture of resin and activator. These types of adhesives are formulated for curing by the application of heat, by an activator, or even, in the case of industrial acrylic with light.

The light curing adhesives are normally used for large volumes in which capital investment for the development of the emission source of light is justified.

Advantages of acrylics:

- High temperature resistance (up to 180º)
- Versatile dosification
- Excellent hydrolytic resistance to aggressive environmental agents
- Minimal surface preparation needed or even zero in the case of metals and plastics
- Excellent price-performance ratio
- Good gap filling capacity (up to 3mm)
- Good physical structural properties and resistance against loads
- Cure times very short
- Allows the union of different materials (metal, wood, glass, plastic), even to each other.

Disadvantages of acrylics:

- Less adhesion to most elastomers
- Odor
- Low inflammation points

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Some areas of application of acrylic adhesives can be:

- Solar heating panels
- Automotive industry
- Structural adhesion on ships and planes
- Brake Shoe adhesion to crowns
- Speaker magnets

6.3.- FLEXIBLE ADHESIVES

6.3.1.- Polyurethanes

Polyurethanes, like epoxies, can be found as bicomponents mixed adhesives as well as monocomponents. These products are based on isocyanate chemistry, resulting from the reaction of an isocyanate with water or with a polyol or an amine in the case of the bicomponents.

The monocomponent polyurethanes polymerize from the outermost layer to the innermost by reaction with moisture, which limits the thickness of the adhesive, curing time increases and reduces its useful life, because as the outermost part of the adhesive is dried worsens the bond to the substrate. Sometimes the application of heat is required to accelerate the curing of the adhesive. Usually these adhesives are used as sealants.

The bicomponent polyurethanes have a wide range of curing times to meet different application requirements.

Polyurethanes wet badly the surfaces, and this requires the use of primers, which react with ambient moisture.

Advantages of polyurethanes:

- Allows bonding a wide range of substrates
- Remain flexible in a temperature range between -40°C and 80°C
- Good chemical resistance
- Can be painted
- Produces very mild odor
- Better resistance to peel than epoxies

Disadvantages of polyurethanes:

- Troubles of safety and hygiene during polymerization
- Primers needed
- Low resistance to UV radiation

Some areas of application of polyurethanes can be:

- Construction and reparation of ships, trailers, containers, doors and windows...
- Transportation and automotive
- Mechanical engineering and machines assembling
- Household appliances
- Ventilation systems

6.3.2.- Silicones

Silicones are single component adhesives whose polymerization reaction generates byproducts that are often volatile. Silicones can be classified according to the type of product released:

- Acetic: release acetic acid, which causes problems of corrosion in certain metal substrates such as copper.
- Alkoxy: release alcohol (usually methanol)
- Aminic: when amine is released

- Oxime: These are special formulations releasing oximes, but with the peculiarity that in this case the reaction by-product is reused again in the polymerization reaction. This is why they are also known as neutral silicones

There are also silicones which cure by UV emission lamps to fix the adhesive on the substrates. Sometimes, this system is used with moisture cure.

<u>Advantages of silicones:</u>

- Provide good adhesion and sealing on various substrates.
- Keeps flexible within a temperature range of -55º C and 250ºC, though some formulations can endure up to 350ºC
- Good durability
- Resistance to moisture, ozone and UV radiation
- Excellent dielectric properties

<u>Disadvantages of silicones:</u>

- Can't be painted
- The acetic silicones produce a penetrating odor (smell of vinegar)
- Low resistance to hot oils, fuels and chlorinated products

Some areas of application of silicones:

- Cracks repair
- Adhesion and sealing of different materials (appliances, tires and hoses, electrical elements, glass ...)
- Avoid leaks
- Electrical insulation
- Coating of conveyors

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Adhesive Selection Guidelines

Characteristics	Standard Epoxies	Urethane	Acrylic	Silicones	Polyolefins (Vinylics)
Adhesive type[a]	L1, L2, F	L, W, HM	L1, L2, W	L1, L2	F
Cure requirement	Heat, ambient	Heat, ambient	Heat, ambient	Heat, ambient	Hot melt
Curing speed	Poor	Very good	Best	Fair	Very good
Substrate flexibility	Very good	Very good	Good	Good	Fair
Shear strength	Best	Fair	Good	Poor	Poor
Peel strength	Poor to fair	Very good	Good	Very good	Fair
Impact resistance	Fair	Very good	Fair	Best	Fair
Humidity resistance	Poor	Fair	Fair	Best	Fair
Chemical resistance	Very good	Fair	Fair	Fair	Good
Temperature resistance (ºC)	Fair	Fair	Fair	Good	Poor
Gap filling	Fair	Very good	Very good	Best	Fair
Storage (months)	6	6	6	6	12

[a] Adhesive type: L1 = Liquid one part, L2 = Liquid two part, F = Film, W = Waterborne, HM = Hot melt.

Figure 6.1.-   Selection guide of adhesives based on their properties.

7. Surface treatments

As above mentioned, sometimes the substrate requires a surface treatment. The adhesion process is a surface phenomenon; consequently any intermediate substances formed (dust, oil…) need to be removed in order to ensure a good bonding. In some cases, the weak layers also need to be eliminated for increasing the wetting capacity of the surface of the substrate and to ensure a better bond.

Metal substrates have surface energies superior to the surface tension of the adhesives, so that they only require a cleaning treatment. On the contrary, polymers have low surface energy, making necessary a chemical modification of their surface to improve wetting. Thermoplastics are generally difficult to bond and need treatments such as flame oxidation, plasma, treatment with an ionized inert gas or the use of primers or adhesion promoters.

Once the surfaces have been prepared, the bonding process must be done as soon as possible in order to avoid the occurrence of new substances. In case that the materials need to be stored, special measures need to be taken in order to avoid the contamination of the substrates.

The surface treatments can be passive or active:

-   Passive surface treatments are those which do not chemically modified the surface. Representative examples are: steam phase degreasing, ultrasonic bath treatment, mechanical abrasion, etc.
-   Active surface treatments, at difference to the previous, do modify the chemistry of the surface of the substrate. These include: plasma treatment, anodizing, etching, corona discharge, flame treatment, etc

7.1.- PASSIVE SURFACE TREATMENTS

7.1.1.- Degreasing

This treatment is used to eliminate greases and oils from the surface of the substrates to be bonded (metals or composites). The specific method depends of the type of substrate. Metallic surfaces can be cleaned by immersion in a bath of a chlorinated solvent, such as trichloroethane, during 30 min or with a cotton impregnated with the solvent. In the case of composites or polymeric surfaces, where release agents are used, ketone and alcohol solutions or detergents are currently applied for their removal.

7.1.2.- Mechanical abrasion

The objective of the mechanical abrasion is to increase the roughness of the surfaces, which improves the wetting of the substrate to the bonding agent, simultaneously to the cleaning of the surface by removal of contaminants and solid particles. This is used with metals and composites. Mechanical abrasion can be performed with sandpaper, wire brushes, sandblasting or mobile rollers, among others. Then, the generated particles which are deposited on the surface need to be eliminated, to that, solvents or clean air jets can be used.

7.1.3.- Ultrasonic baths

When using ultrasonic cleaning treatments, the substrate is introduced in a tank which contains a solvent or a mixture of solvents. The effectiveness of the liquid on the surface to be treated is strengthening by the ultrasonic wave's radiation. This procedure allows a high quality cleaning of the surfaces, as particles in areas of difficult access can be reached. The type of solvent to be used depends on the characteristics of the contaminant.

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7.2.- ACTIVE SURFACE TREATMENTS

7.2.1.- Chemical Treatments

Chemical treatments are ideal in applications where special surface preparations are necessary, to increase surface energy above the adhesive, in addition to providing a large increase in the life of the bonding. However, they require rigorous controls due to waste generation and modification of the intrinsic properties of the materials.

There are several types of chemical treatments depending on the type of adhesive and substrate.

7.2.2.- Low pressure plasma treatment

This treatment makes use of a plasma produced by ionization of a gas integrated by ions and electrons positively charged, which when collapse they produce a large amount of energy. In the low pressure plasma treatment, the gas is excited, with a high frequency and a high voltage, between two electrodes in a low pressure chamber. The possibility to use different types of plasmas (Argon, ammonia, nitrogen or oxygen) makes this process adequate for different materials. The oxygen of the air produces the best results, as it reacts with contaminants and breaks long chain molecules.

By his procedure, a triple action is achieved, as we not only clean the surface of the substrate, but we also improve the surface roughness and activate a surface initially inert.

7.2.3.- Flame treatment

In this process a flame of a gas (fuel gas) or gas/oxygen is applied to the surface of the substrate, producing a partial oxidation and thus increasing its surface energy. It is easy to control and adjust the gas/oxygen relation, the frequency, the exposure time and the proximity of the flame to the substrate.
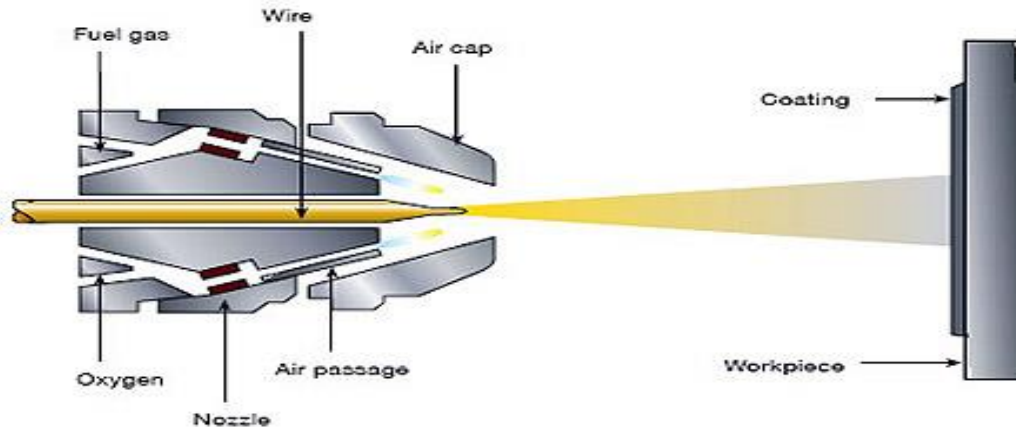
Figure 7.1.- Example of superficial flame treatment.

7.2.4.- Corona discharge

This procedure is also a low pressure plasma process. In this case, the plasma is generated by applying a high voltage between two metallic electrodes with a defined geometry. The substrate is placed in the gap between the electrodes and treated with the ionized gas. This process activates the substrate and increases its surface tension. At difference to the flame treatment, this can only be used with low thickness substrates
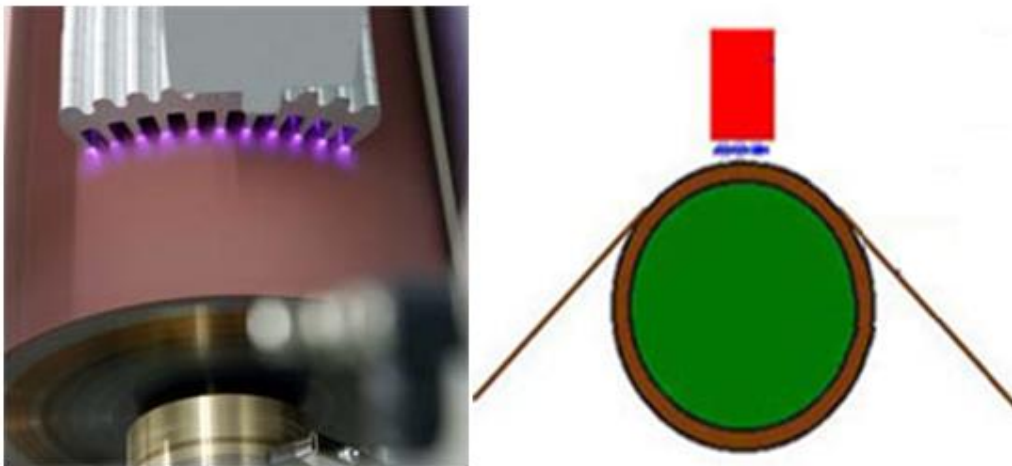
Figure 7.2.- Example of corona superficial treatment.

7.2.5.- Primers

These are substances based on diluted polyurethanes and silanes applied on the substrate surface in order to improve the interaction between the substrate and the adhesive and to protect the surface on which it is applied. The type of primer used, acting as an intermediate layer, depends on the type of the adhesive and the substrate.

In some cases, where an exhaustive control of the production process cannot be made, primers are used to avoid possible failures.
In addition, this type of treatment greatly increases the life of adhesion.

Substrate	Solvent Cleaning[a]	Intermediate Cleaning	Chemical Treatment or Other
Aluminum	Chlorinated solvent, ketone, or mineral spirits[b]	Detergent scrub	Sulfuric (96%) acid/sodium dichromate (77.8/22.2 pbw) solution at 25°C for 20 min; rinse with tap water followed by distilled water, dry for 30 min at 70°C
Beryllium/copper	Chlorinated solvent, ketone, or mineral spirits[b]	Wet abrasive blast	—
Copper	Chlorinated solvent, ketone, or mineral spirits[b]	Dry abrasion or wire brushing	Nitric (69%) acid/ferric chloride/distilled water (12.4/6.2/81.4 pbw) solution at 21–32°C for 1–2 min; rinse in tap water followed by distilled water; dry at 65°C maximum
Steel (stainless)	Chlorinated or aromatic solvent[b]	Heavy-duty alkaline cleaner	Nitric (69%) acid/distilled water (20/80 pbw) solution at 21–32°C for 25–35 min; rinse with tap water followed by distilled water; dry at 65°C maximum
Steel (mild)	Same as stainless	Same as stainless	Ethyl alcohol (denatured)/orthophosphoric (85%) acid (66.7/33.3 pbw) solution at 60°C for 10 min; rinse in tap water followed by distilled water; dry for 60 min at 120°C
Titanium, titanium alloys	Ketone or aromatic solvent	Mild alkaline cleaner or wet abrasive scour	Nitric (69%) acid/hydrofluoric (60%) acid/distilled-water (28.8/3.4/67.8 pbw) solution at 38–52°C for 10 to 15 min; rinse with tap water followed by distilled water; dry 15 min at 71–82°C; brush off carbon residue with nylon brush while rinsing
Ceramic	Ketone solvent	—	Sulfuric (96%) acid/sodium dichromate/distilled water (96.6/1.7/1.7 pbw) at 20°C for 15 min; rinse with tap water followed by distilled water; dry at 65°C maximum

[a] Immerse, spray, or wipe.
[b] Or vapor degrease with chlorinated solvents.

Figure 7.3.- Surface treatments of common metals and ceramics.

Substrate	Solvent Cleaning[a]	Intermediate Cleaning	Chemical Treatment or Other
Acetal (Delrin)	Ketone solvent	Dry abrasion or wet or dry abrasive blast	Sulfuric (96%) acid/potassium dichromate/distilled water (88.5/4.4/7.1 pbw) solution at 25°C for 10 sec; rinse with tap water followed by distilled water and dry at room temperature
ABS	Ketone solvent	Dry abrasion or wet or dry abrasive blast	Sulfuric (96%) acid/potassium chromate/distilled water (65/7.5/27.5 pbw) solution at 60°C for 20 min; rinse with tap water followed by distilled water; dry with warm air
Polycarbonate (PC)	Alcohol	Dry abrasion or wet or dry abrasive blast	—
Polyethylene (PE) and polypropylene (PP)	Ketone solvent	—	Sulfuric (96%) acid/sodium dichromate/distilled water (88.5/4.4/7.1 pbw) at 70°C for 60 sec; expose surface to gas burner flame until the substrate is glossy. Can also be treated with corona discharge or flame.

[a]Immerse, spray, or wipe.

Figure 7.4.-   Surface treatments of common plastics

8. Advantages and disadvantages of adhesives

Adhesive bonds have the following advantages and disadvantages compared to other binding mechanisms:

8.1.- ADVANTAGES

- Uniform stress distribution
- Improves the final appearance of the product
- No corrosion occurs, as in the case of joints by metal parts.
- It doesn't produce any deformation in the substrates, reducing the manufacturing cost
- Reduction of the weight in the final product
- Reduce the number of components
- High resistance to impact and fatigue
- Better design flexibility
- It allows the union of different materials
- Rigid unions

8.2.- DISADVANTAGES

- Poor against peel strength and through-thickness
- It needs time to be cured
- Inability to disassembly
- Need of surface preparation
- Sensitive to environmental degradation (temperature, humidity ...)
- May require expensive tools
- Maybe of environmental concern

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9. Sandwich Structures

Probably, due to its simplicity of design, the first composite structures were sandwich type. These joints are made up of two thin and resistant sheets (skins or coatings) between which is placed a thick and lightweight core. Both materials can be bonded together by means of an adhesive.

These structures are designed so that the sheets absorb the bending stresses and axial forces of tension and compression. For its part, the core separates the sheets together to increase the inertia in bending and supports the shear stress. By increasing the distance between the sheets an increased flexural stiffness is obtained, just as we will see later.
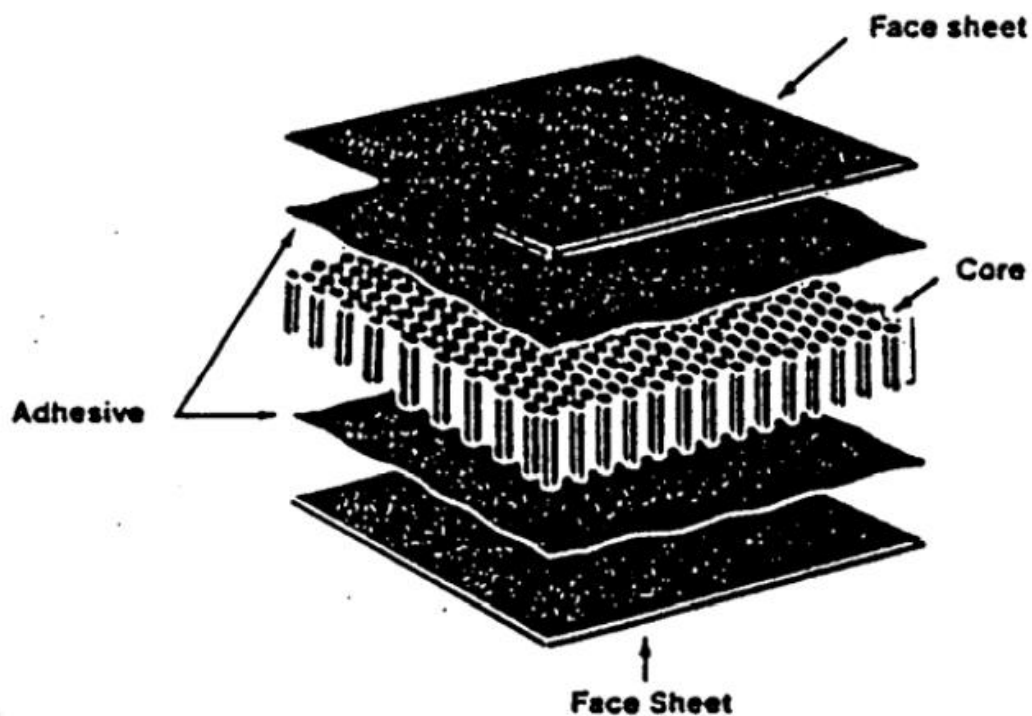

Figure 9.1.-   Scheme of a sandwich structure

Nowadays, this design has achieved a great importance in the automotive, aerospace, shipbuilding and construction sectors, as they allow obtain structures of high rigidity, which increases its resistance to bending, and lightweights.

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Furthermore, these structures offer the following advantages:

- Great thermal insulation, due to the low thermal coefficients presenting the cores.
- Good resistance to fatigue, which is due to continued binding of the skins to the core, which favors the reduction of residual stresses.
- Obtaining of smooth and soft surfaces.
- Good impact resistance.
- Low Cost and manufacturing time.

However, just like all structures seen previously, the sandwich panels have a number of disadvantages, among which we highlight:

- Possibility that separation occurs by shearing or peeling, of the joint between layers and core. This will depend on the type of adhesive used.
- High Risk of catching fire, due to bad fire resistance of several of the materials chosen for the core.
- Local subsidence of the structure, which can occur when the skins are too thin, causing the failure of the core by compression.
- Low Sealing against water, which can cause in first place the degradation of the adhesive and then the core.
- Although probably the biggest problem with this type of joints is produced in uniting the various component materials.

9.1.- INFLUENCE OF THICKNESS OF THE CORE

The flexural rigidity and lightness improve as we increase the thickness of the core just as we can see in the following table:
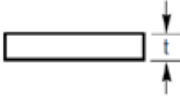
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	Sheet		
relative stiffness	100	700 7 times stiffer	3700 37 times stiffer
bending strength	100	350 3.5 times more resistant	925 9.25 times more resistant
relative weight	100	103 3% weight increase	106 6% weight increase

Figure 9.2.- Influence of thickness of the core in a sandwich structure

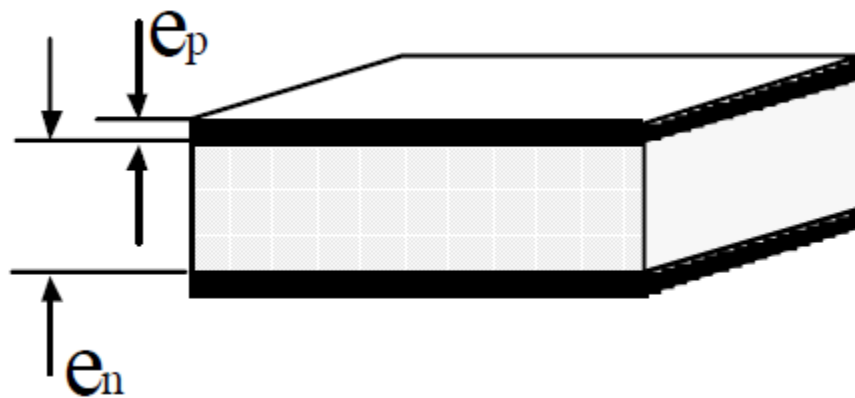Nonetheless, the thicknesses must be within certain limits:

Figure 9.3.- Thickness scheme of a sandwich structure

$10 \leq \dfrac{e_n}{e_p} \leq 100$

$0{,}25\text{mm} \leq e_p \leq 12{,}7\text{mm}$

$0{,}025\text{mm} \leq e_a \leq 0{,}2\text{mm}$

$20\dfrac{Kg}{m^3} \leq \gamma_n \leq 1000\,\dfrac{Kg}{m^3}$

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Where:

e_p Sheet thickness

e_n : Core thickness

e_a : Adhesive thickness

γ_n : Density core

9.2.- TYPES OF SANDWICH BONDS

In practice we can find different sandwich type structures, depending on the core distribution.

In the table below we can see the most common structures, as well as some of the materials used to manufacture their elements:
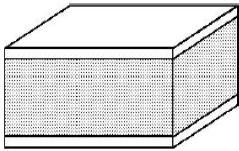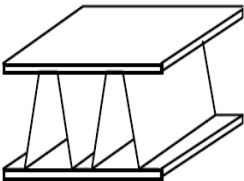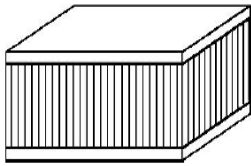
	Face sheet materials	Core materials	Core distribution
	Metals Laminates Plywood thermoplastic	Polyurethane foam Polystyrene foam	Expanded
	Cement Metals Laminates	Metals composite materials	Ribbed
	Plywoods Laminates Aluminium	Cardboard honeycomb Wood Aluminium honeycomb Thermoplastic	Honeycomb

Figure 9.4.-   Types of sandwich structures

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Probably the three types mentioned in the table, the honeycomb is the most used, and therefore, in the next chapters we will focus on this structure to learn more about it.

10.Honeycomb Core

It's about structures whose core has honeycomb geometry, this minimizing the amount of material used. The resistance of the assembly will depend largely on the size of the core, the material used and the number of cells it will contain.

10.1.- COMPONENTS[5]

As we have discussed, the sandwich types structures are formed by two coatings covering the core.
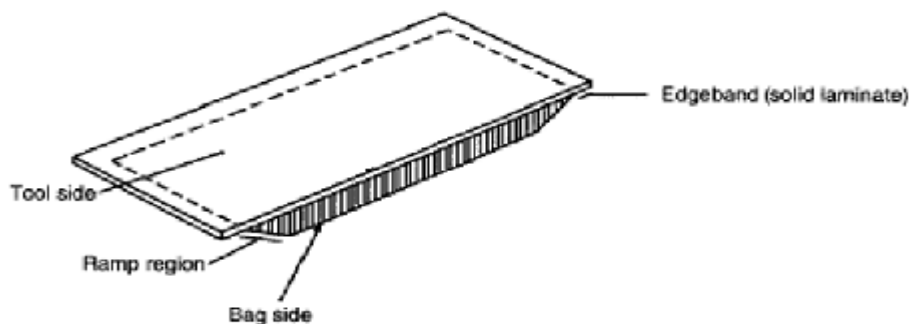
Figure 10.1.- Scheme of a sandwich structure with honeycomb core

As we can see in the picture above, the coatings can be called as tool side or bag side. This name is because in the manufacturing process a vacuum bag is used. The tool face is over the manufacturing tool and the bag face is in contact with the vacuum bag.

The bag face follows the contour of the core, forming a slope until the core ends and arrive to the tool face. The area where the tool face and bag face are joined is called track, and the area where the core has a constant thickness area is called "bulk".Next we explain in detail each of the above items.

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[5] We used contents used by ML Romero Galera in Estudio del comportamiento estructural de paneles sándwich empleados en el canerado de aviones comerciales.

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10.1.1.- Sheets

The skins or coatings are composite materials laminated formed by bonding a resin, constituting the matrix, and a stronger material (fibers interwoven in two directions). These materials are supplied as rolls of l prepreg material (impregnated fiber matrix), varying weights, widths and thicknesses.
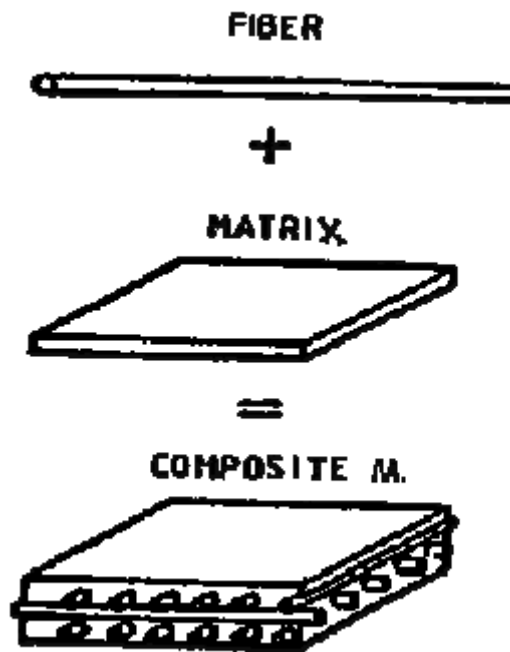
Figure 10.2.- Composite material

These laminates with intertwined bidirectional reinforcement in perpendicular directions are called tissues. The mechanical properties are determined by the directions of the reinforcements; weft and warp. The weft is perpendicular to the longitudinal edge, while the warp is parallel thereto.

The following figure shows a roll of composite tissue, where can differentiate weft and warp.

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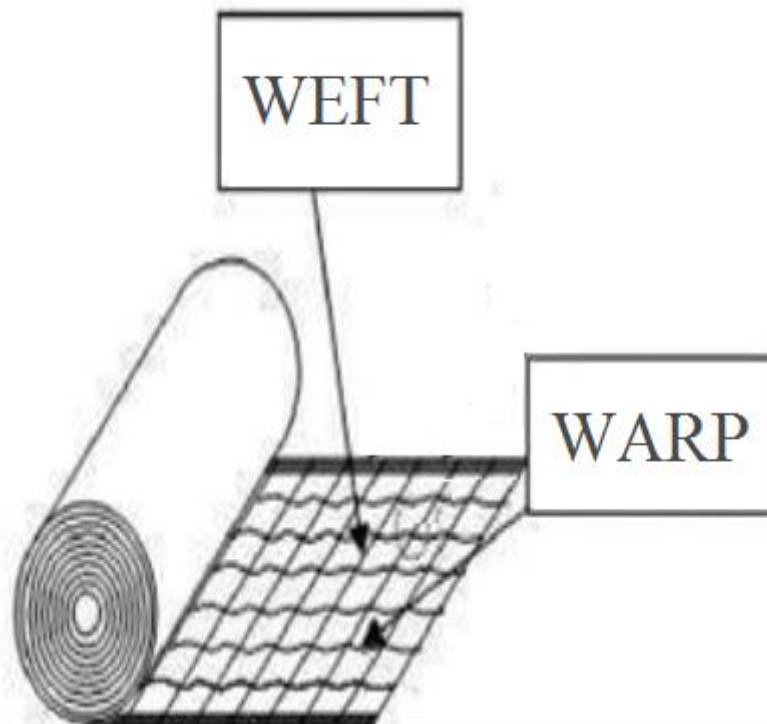
Figure 10.3.- Tissue coil

In such materials, the fibers endure the loads, while the primary function of the matrix is to hold together and protect these fibers. Therefore, the mechanical properties of a tissue are defined by the warp and weft directions.

The most commonly used fibers are carbon, glass, boron and organic (recorded as Kevlar). For the matrix is generally used epoxy resins and polyester.

The characteristics that are often of interest in composite materials are:

- Great specific strength
- High specific stiffness
- Low density
- Bad electrical conductors
- Corrosion resistant
- Long fatigue life
- Damping vibrations

- Thermal and acoustic insulation

- Abrasion resistance

- Ability to design and modify the mechanical properties based on their anisotropy

They also have certain drawbacks, among which are:

- High cost of the material

- High sensitivity of the mechanical properties to changes in temperature and humidity

- Technologically complex manufacturing processes

- Equipment and manufacturing facilities high cost

- Possibility of inducing galvanic corrosion in contact with metallic materials

- High effort in process control processes

- Limited life before polymerization

10.1.2.- Core

As we mentioned above, the core can be defined as that element of low density and low mechanical characteristics that separates the coatings in a sandwich structure.

10.1.2.1.- Honeycomb core characteristics

There are several types of honeycomb, but they all have as common characteristic to have hollow cells separated by very thin vertical walls. The parameters used to define any core of this type are:

- Cell: Figure or geometric shape that is repeated throughout the core. The cells normally have hexagonal shape, but we can also find rectangular, or even in shaped of clover or mushroom.

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hexagonal	rectangular	mushroom
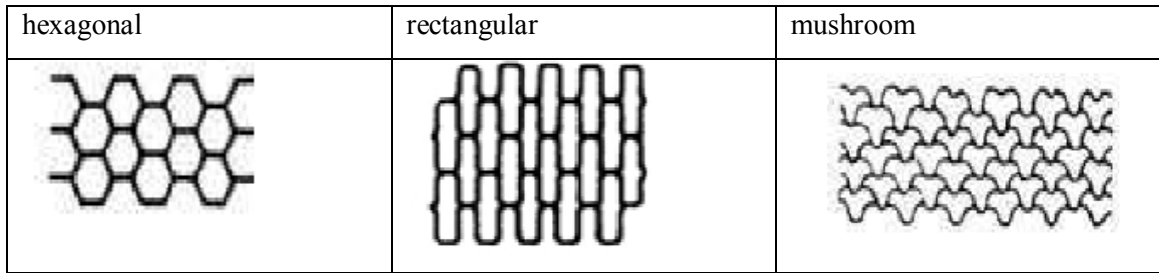
Figure 10.4.- Types of honeycomb core cell

− Node: bonding area between cells.

− Diameter or cell size (Ø): distance between the opposite sides of a cell or diameter of the circle inscribed in it.

− Thickness of the sheet that form the cell (e).

− Longitudinal direction or ribbon (L): direction to the sense of expansion of the core or straight line parallel to the node.

− Transverse Direction (W): direction perpendicular to the node.

− Height core (T): distance between the faces of the core

− Density: depends on the thickness of the sheet, the used material and diameter of the cell.

Figure 10.5.- Scheme of core cells

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10.1.2.2.- Honeycomb core materials

These cores can be made of different materials (metal or non-metal) depending on the application to be developed.

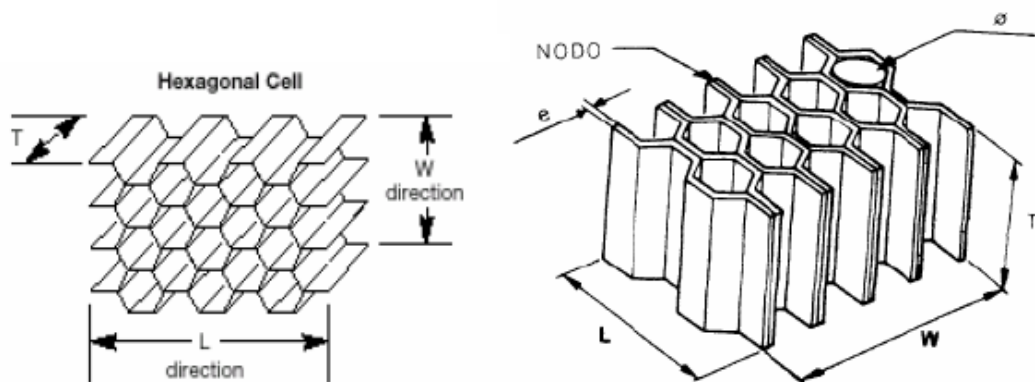Then we show some of the more common materials, with which can be manufactured these cores and their corresponding advantages:

Metallics

Among the metallic materials we can find different aluminum alloys, depending on the sector in which it is to be used, and stainless steels, among others. This type of material exhibits excellent resistance to fire, to temperature, to corrosion and to moisture as well as high rigidity and low weight.

Non-metallics

Within this group we can find:

- Aramid fibers (manufactured by Dupont Nomex), this material is a great thermal and electrical insulator, having a high resistance to fatigue, creep, compression loads, temperature and fire. In addition, it supports almost all adhesives and has very low density.
- Thermoplastics, the structures made from these materials have a core with 3 orientations vs. the 2 of the others, thus making its properties more uniforms. Also it presents a high stiffness, resistance to corrosion by moisture, sound damping and vibration, good energy absorption and high thermal resistance (thermo deformable).

Other non-metallic materials can be: carbon fiber, kevlar fabric and kraft paperboard with phenolic resin.

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As we have seen, the honeycombs possess unique mechanical and physical properties depending on the material with which they have been manufactured. Therefore, we can ensure that the properties of this type of cores are closely related to the type of material that has been used to produce it. Some of common characteristics of these cores types are:

- Excellent resistance to compression
- Good resistance to shear stress.
- Great lightness
- Some materials, like polypropylene, do not absorb water, which makes them suitable for applications in wet environments.
- Some materials are completely resistant to corrosion, salts, fungi and moisture
- Great energy absorption
- Resistant to fatigue even with small thicknesses
- Excellent thermal properties.
- One of the most important advantages is that most of the materials with which it is built are recyclable
- It's easy to cut, paste, to weld and to handle, among others.

10.1.3.- Adhesive

Depending on the procedure used to manufacture the sandwich can be used a film of adhesive or not. If coatings are cured and then are attached to the core, it is necessary to use an adhesive layer between each coating and the core. However, if it is manufactured by a co-curing of the coating and the core, it is not necessary to use an adhesive, since the resins of the fiber sheets can act as binding mean between the two elements.

10.2.- ASPECTS TO CONSIDER

As we mentioned in previous chapters, for obtain effective an union it is necessary to consider certain aspects when performing the joint design. Among them we highlight:

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-The Adhesive must achieve a strong bond between the core and the sheets, this assumes that should flow enough as to form the film without the occurrence of leaks by the internal cavities of the cells. An effective bonding can be achieved with a spray application system, self-cleaned and low pressure. For such structures recommended employing rigid adhesives as epoxies.

-The cell size should be appropriate, because if they are too large the bonding area will be too small and this will affect the bond strength. Conversely, cells too small can be assumed an excessively high economic cost without achieve great advantages.

-The physical properties and the thickness of sheets are also a very important factor, as in the case of the core, are closely related to the material used. In addition, we can increase its rigidity increasing its thickness, within certain limits for will not make too heavy the set. Below is a table with the properties of the most used materials for the construction of the layers in this structures type:

FACING MATERIAL	TYPICAL STRENGTH Tension/Compression MPa	MODULUS OF ELASTICITY Tension/Compression GPa	POISSON'S RATIO μ	TYPICAL CURED PLY THICKNESS mm	TYPICAL WEIGHT PER PLY kg/m²
Epoxy UD CARBON tape (0°) 60% volume fraction	2000 / 1300	130 / 115	0.25	0.125	0.19
Epoxy UD GLASS tape (0°) 55% volume fraction	1100 / 900	43 / 42	0.28	0.125	0.25
Epoxy WOVEN CARBON (G793-5HS) 55% volume fraction	800 / 700	70 / 60	0.05	0.30	0.45
Epoxy WOVEN ARAMID (285K-4HS 60% volume fraction	500 / 150	30 / 31	0.20	0.20	0.27
Epoxy WOVEN GLASS (7781-8HS) 50% volume fraction	600 / 550	20 / 17	0.13	0.25	0.47
Phenolic WOVEN GLASS (7781-8HS) 55% volume fraction	400 / 360	20 / 17	0.13	0.25	0.47
ALUMINIUM Alloy 2024 T3 5251 H24 6061 T6	Av. Yield 270 150 240	Av. 70	0.33	0.50	1.35
STEEL carbon 1006 1017	Av. Yield 285 340	Av. 205	0.30	0.5	4.15
Exterior PLYWOOD Fir	30 / 35	Av. 9	0.1	12.7	6.3
Tempered HARDWOOD Teak	110 / 40	Av. 12	0.1	12.7	8.5

Figure 10.6.- Properties typical of sheets materials

-The objective of using these structures is to obtain rigid structures of low weight, therefore, must be achieved sets more lightweight possible.

-In this type of structure, the sheets are not continuously over the core, but each cell leaves a portion of the sheets without support. This is a critical design parameter that depends on the type of cell geometry and properties of the skins.

-As we mentioned earlier, the sheets can be cured separately and then join the core or be co-cured with the core in a single operation. The first type of procedure ensures sheets with a good surface finished, but can present adjustment problems between the coatings and the core. The second type of procedure, however, usually has a poor surface finished but the adjust with the core is much better. The superficial finished in this case can be improved using a second sheet co-cured with the first coating or curing in a later cycle.

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11.Mechanical behavior in a sandwich structure

When a load is applied to this type of structures, each element has a specific function. The sheets resist the loads in the plane and bending moments, providing most of the bending stiffness as they have a higher modulus of elasticity than the core and are located at a greater distance of the neutral axis of the structure. The core provides the necessary distance between the sheets, increasing the bending stiffness, and endured the shear stresses, which transmitted at the faces as a moment about the neutral axis of the structure. It also supplies stiffness to shear and stabilize the loads, preventing that the coatings buckling.
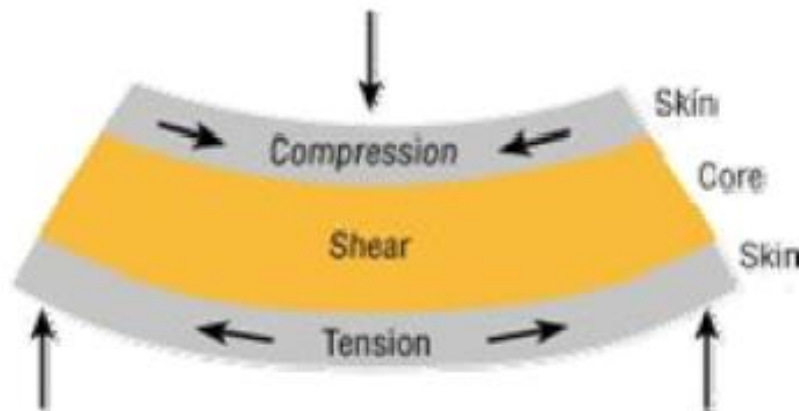
Figure 11.1.- Stresses of a sandwich structure

12. Failure modes of a sandwich structure [6]

Then, due to the complexity of explaining this point, it does explain as

In the case of sandwich structures we can find three types of failures according to the origin, which can occur independently or combined:

- Insufficient resistance
- Local instabilities
- Global instabilities

12.1.- INSUFFICIENT RESISTANCE

Within this group we find the faults that occur in the sheets and core, this happens when the values of ultimate strength of the material is exceeded.

The parameter that determines whether there has been failure of a component is called reserve factor (RF). When this is less than one, the component being analyzed is failing according to the failure mode associated with that factor.

- Failure of the sheets:
  - Break by plane stress
  - Break by interlaminar shear

---

[6] Due to the complexity of explaining this point, it does explain as Romero Galera M.L**.** in Estudio del comportamiento estructural de paneles sándwich empleados en el canerado de aviones comerciales.

- Failure of the Core:

  - Failure by transversal shear

    – Shear core

    – Debonding of the face sheets

  - Crushing of the core

  - Plane tensions in the ramp region

12.1.1.- Break of the sheets by plane stress

Breakage of sheets occurs when the tension at one of the faces exceeds the allowable stress of tensile or compression of the material. This may be due to insufficient thickness of the skins or core.
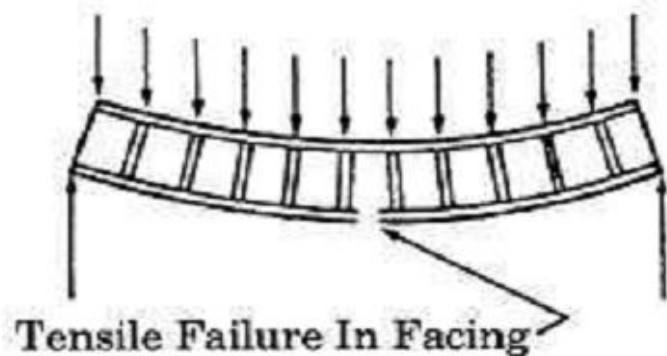

Figure 12.1.- Break by plane stress

12.1.2.- Break of the sheets by interlaminar shear

This failure does not usually occur because the shear stresses in the skins are very low, being more probable this type of break in the core.

The reserve factor for the rupture by interlaminar shear, RF_{ILSS}, is calculated:

$$RF_{ILSS} = \frac{\tau_{ILSS}}{\sqrt{\tau_{zx}^2 + \tau_{yz}^2}} \qquad (11.1)$$

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Where:

τ_{ILSS} = interlaminar shear strength (MPa)

τ_{zx}= xz shear stress (MPa)

τ_{yz} = yz shear stress (MPa)

12.1.3.- Failure of core by shear

It is due to the core has a lower shear resistance to the applied , which may be because the thickness of the panel is too low.
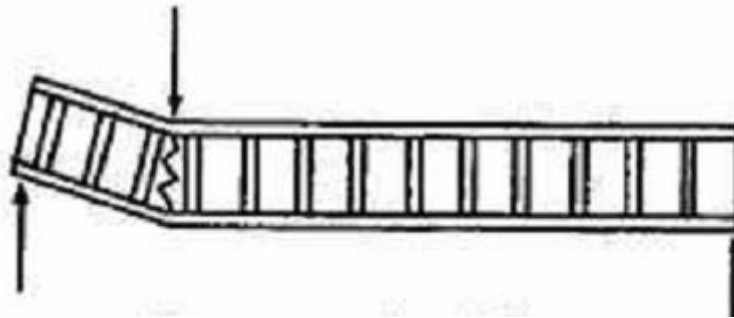

Figure 12.2.-   Failure of core by shear

The break for this type of failure can occur in regions of the bulk area adjacent to the ramp (also in the same ramp), or inner regions of the panel due to the presence of stress concentrators.

The reserve factor for this type of failure is calculated:

$$RF_{cshear} = \frac{1}{\sqrt{(\frac{\tau_{core\_zx}}{\tau_{zx\_ult}})^2 + (\frac{\tau_{core\_yz}}{\tau_{yz\_ult}})^2}} \tag{11.2}$$

Where:

τ_{core_zx} = zx shear stress in the core (MPa)

τ_{zx_ult} = zx ultimate shear stress in the core (MPa)

τ_{core_yz} = yz shear stress in the core (MPa)

τ_{yz_ult} = yz ultimate shear stress yz in the core (MPa)

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12.1.4.- Debonding of the sheets-core

The debonding of the skins of the core could only occur by shear loads. This only occurs by an adhesive or cohesive failure of the adhesive. This bond strength (both adhesive and cohesive) is called peel strength.

Therefore the reserve factor will be:

$$RF_{deb} = \frac{\tau_{deb}}{\sqrt{\tau_{zx}^2 + \tau_{yz}^2}} \tag{11.3}$$

Where:

τ_{deb} = Peel strength (MPa)

τ_{zx} = zx shear stress of the skin-core bonding (MPa)

τ_{yz} = zx shear stress of the skin-core bonding (MPa)

12.1.5.- Core crush

Caused by a low resistance of transverse compression of the core. It can be a located fault, due to a compressive point load acting in the bulk zone, as shown in the following figure:
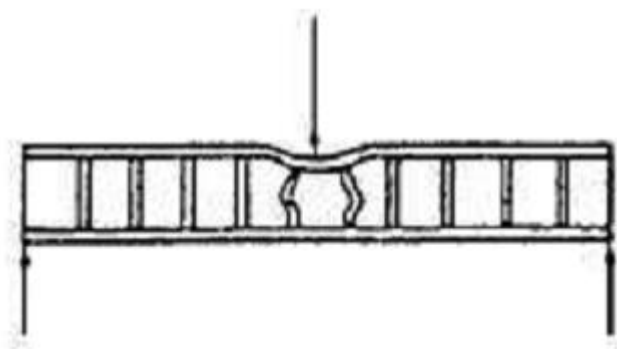

Figure 12.3.- Core crush

The following expression allows to determine the reserve factor for this type of failure:

$$RF_{compression} = \frac{F_{cc}}{\sigma_z} \tag{11.4}$$

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However, if it were of a general failure (e.g. due to bending), the core must endure the bending of both faces of the panel, so that it induces a compressive force.

Figure 12.4.- Rupture by bending of the core

This failure is found where maximum bending moments are located. Obtaining the following expression:

$$RF_{crush} = \frac{F_{cc}}{f_{crush}}$$ (11.5)

Where:

f_{crush}= Crushing stress in the core (MPa)
F_{cc} = Allowable stress of crush in the core (MPa)

This failure criterion is not usually used, since in the areas of greater bending occurs before sheets breakage that the core crush.

12.1.6.- Failure of the core by tensile or compression in ramp areas

Although the failure by compression or tensile in the core may occur at any point on the surface if the loads are high enough, the points where this failure is most critical are the areas where the coatings change direction. This is because in these areas the plane loads of the coating have a component normal to the core.

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Figure 12.5.- Plane stress in areas of change direction of the bag face

The tensions in these areas, called flatwise, depending on radius that form the fabrics of the bag face when changing direction at the beginning and end of the ramp, are:

$$F_{flat} = \frac{N_{xb}}{\cos(\alpha)R}$$
(11.6)

Where:

F_{flat} = Tensile or compressive stress in the radius of ramp (MPa)

N_{xb} = Strength in the bag face per unit length (N/mm)

R= Radius of curvature of the fabrics in the bag face at the beginning and end of ramp (mm)

This tension should be less than the allowable stress of crush of the core in the event that the loads in starting and ending zones of the ramp cause the compression of the core. In the event that occurs the core traction in the same areas seen before, the flatwise stress must be less than the tensile allowable of the adhesive.

12.2.- LOCAL INSTABILITIES

They are those in which one element, one or both faces, the core or union, fail separately.

12.2.1.- Buckling sheets (dimpling)

Is a local buckling with the wave enough short to stay confined in the individual cells of the core. This only occurs in cell core, when the faces are very thin and the cell size is very large.

This failure can be not catastrophic while the amplitude of the deformations not grows enough as to move from one cell to another, producing an accumulation of wrinkles that can even remain after removal of the load.
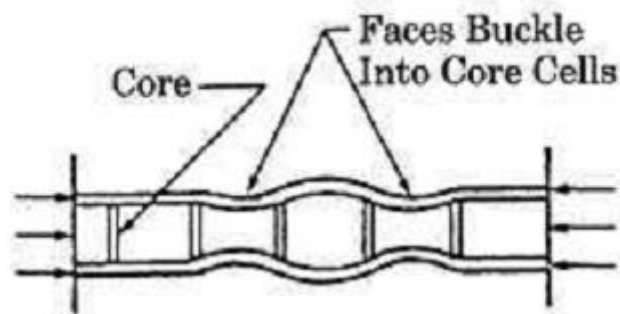

Figure 12.6.- Failure by dimpling

The instability by dimpling occurs under compressive loads or shear in the plane. The critical zone is usually the center of the panel, where the bending moments are maximums.

Next are shown the reserve factors for each cases:

a) Under compression loads:

$$RF_{Cdimple} = \frac{F_{Cdimple}}{f_{xf} + f_{yf}}$$

(11.7)

b) Under shear loads in the plane:

$$RF_{Sdimple} = \frac{F_{Sdimple}}{f_{xyf}}$$ (11.8)

c) Under load combination of compression and shear in the plane:

$$R_c = \frac{(f_{xf} + f_{yf})}{F_{Cdimple}}$$ (11.9)

$$R_S = \frac{f_{xyf}}{F_{Sdimple}}$$ (11.10)

$$RF_{dimple} = \frac{2}{R_C + (R_C^2 + 4R_S^2)^{\frac{1}{2}}}$$ (11.11)

Where:

$F_{Cdimple}$ = Critical stress of buckling by intercellular compression (MPa)

f_{xf} , f_{yf} y f_{xyf} = Tensions in the plane for the face that is being tested (MPa)

$F_{Sdimple}$ = Critical stress of Buckling by intercellular shear (MPa)

12.2.2.- Sheets Buckling and crushing or debonding of the core (Winkiling)

It is a local buckling, of one side or both, with a very short wave length, but not enough as to stay confined in individual cells of the core. The buckling may occur inward or out depending on the relative strengths of the core to compression and of the adhesive to tensile. Depending on direction where buckling occurs will produce: a core crush, tear the core, or separation of the faces and the core caused by a failure of the bond. The wrinkling is a catastrophic failure mode.
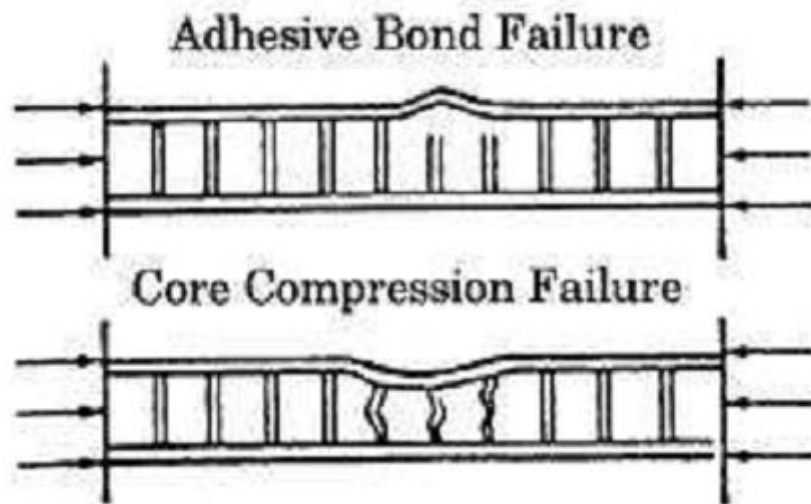
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Figure 12.7.- Failure by wrinkling

The critical stress of wrinkling depends on the resistance and rigidity of the core, the properties of the bonding material, and of the initial eccentricity, or corrugations, of the faces.

This type of failure occurs under compressive loads or shear loads in the plane, and the critical location is usually the center of the panel, where the bending moments are maximums.

Next are shown the reserve factors for each case:

(The following equations have been contrasted with values of tests for flexible cores for very rigid metal cores can provide non conservative results)

a) Under compression loads:

The reserve factor is calculated as follows when f_{yf} is the maximum compression stress. When the maximum compression stress is f_{xf} the exponent should appear in the term of y.

$$RF_{Cwrinkle} = \frac{1}{\left(\frac{f_{xf}}{F_{xfwrinkle}}\right)^3 + \left(\frac{f_{yf}}{F_{yfwrinkle}}\right)} \qquad (11.12)$$

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b) Under shear loads in the plane:

$$RF_{Sfwrinkle} = \frac{F_{Sfwrinkle}}{f_{xyf}}$$
(11.13)

Where:

$F_{xfwrinkle}$ y $F_{yfwrinkle}$ = Allowable stresses of wrinkling for faces (MPa)

f_{xf} , f_{yf} y f_{xyf} = Tensions in the plane for the face that is being tested (MPa)

$F_{Sfwrinkle}$ = Allowable stresses of wrinkling to shear for the faces (MPa)

12.3.- GLOBAL INSTABILITIES

Are those in which occur a generalized failure of the panel

12.3.1.- Global buckling

The global buckling of a sandwich structure may be caused by a low thickness of the panel or by a shear stiffness of the core too low. Skins and core remain intact in this type of failure.
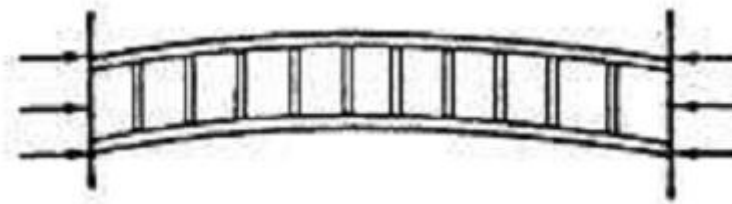

Figure 12.8.-   Global buckling of a sandwich structure

Although there analytical formulations to obtain the critical buckling load for panels with simple geometry and load combinations , the usual procedure for analysis is through the finite element method (FEM).

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12.3.2.- Buckling by core shear

Sometimes this failure mode is considered as local, although in reality it is a form of general instability where the buckling wave length is too short because the transverse shear modulus of the core is very low, which usually occur with low density cores. Also it can produce a shear failure at the union of the core and the coatings, by low shear strength of the adhesive.
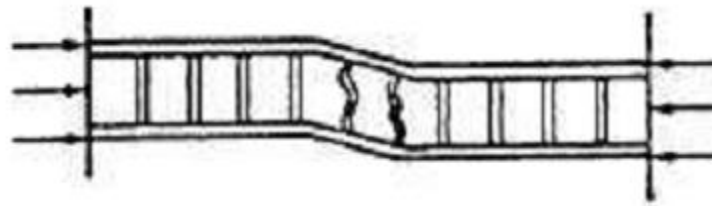

Figure 12.9.- Buckling by core shear

The reserve factors for this type of failure are calculated for each individual direction, because an equation that properly relates the biaxial and shear loads is unknown:

$$RF_{xcrimp} = \frac{F_{xcrimp}}{f_{xf}} \tag{11.14}$$

$$RF_{ycrimp} = \frac{F_{ycrimp}}{f_{yf}} \tag{11.15}$$

$$RF_{xycrimp} = \frac{F_{xycrimp}}{f_{xyf}} \tag{11.16}$$

Where:

F_{xcrimp} , F_{ycrimp} y $F_{xycrimp}$ = Allowable stresses of shear of the core for each direction (MPa)

f_{xf} , f_{yf} y f_{xyf} = Tensions in the plane for the face that is being tested (MPa)

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Figure 1.4: own production

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Figure 2.1: Seminario sobre adhesivos. **(10)**

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Figure 3.15: Composites manufacturing: Materials, Product and Process Engineering, Chapter 9: Joining of composite materials. **(3)**

Figure 4.1: Olmo M., Nave R. (2014): *Hyperphysics Is Hosted By The Departament Of Physics And Astronomy. La tensión superficial y sus efectos.* Available in: http://hyperphysics.phy-astr.gsu.edu/hbasees/surten.html)**.** [View:2/6/2015]

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Figure 6.1: Metalizadora sifone. *Thermal spray process*. Available in: http://www.metalizadorasifone.com.ar/proceso.html. [Consulta:4/6/2015]

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