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Design of Composite Material Structures

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Abstract

The basic rules and principles for designing structures with composite materials are briefly and intensively presented. The proposed design steps are explained. For preliminary design, use of quasi-isotropic properties is proposed. The validity of this proposal will be reported by separate papers.

1. Introduction

The basic principles involved with design of structures made of composite materials are same as those of isotropic materials such as steel. If we consider theories related with composite structures are for the general cases, those with steel belong to a special case of homogeneity and isotropy of materials.

Extensive and brief review on classical mechanics and elasticity is given by the author in his recent book(1). These classical theories and methods of analysis can be used for the composite structures as long as the constitutive, i.e., stress-strain, relationship takes into account the characteristics of material anisotropy.

The same basic design knowledge and technique used for other materials can be applied to the composite structures. The reinforced concrete is a good example of a composite material. However, a design engineer working for the first time with composites often carries a metal mentality which may cause a perilous result. The implementation of accurate design methods for steel structures has required a century's researches and experiences. The ranges of composite materials are so wide and new noble materials are reported almost day by day and the designer of the future will have to be involved with material specifications to control formulation, form and dimension of the element, and the manufacturing process. In fact, concrete design engineer is doing such things since long time ago.

2. Basic Rules for Design

The basic rules for designing with composites can be summarized as follows.

As with any material, it is important to know the loads as accurately as possible. Steel has uniform stiffness in all directions. In a composite, the maximum stiffness and strength are obtained in the longitudinal fiber direction, i.e., on-axis direction. The matrix binds the fibers and bonds the laminae. The lower limit of the transverse stiffness is close to that of the matrix. The shear strength is less than the transverse strength. A composite structural member designed for tension can not be loaded by torsion. After resolving the loads into in-plane stresses, the optimum laminate configuration has to be designed. It is advised that the normal to the plane shear loading should be avoided. A composite element designed to replace a metal element should not have identical shapes. The composite elements shapes are, in general, significantly different from those of metal elements. This is the reason why the author declares that the composite structures belong to the fifth basic concept of structures. There is good flexibility in designing with composites. For each type of load, such as tension, compression, shear, or torsion, we can simply add features to take care of such kind of loads. We can select the parameters which control the mechanical behavior. For metals, for example, the Young's modulus is the same into all directions, and can not be changed even in the direction of the least stresses. With composites, we can change the mechanical properties, even without changing the geometry of the structural element, by simply changing the fiber type, volume, and orientation, and the matrix.

There are endless list of both matrices and reinforcements. However, there are some guidelines. Use glass-fibers for low-cost strength and large structures. If stiffness is important, use carbon fibers. For impact resistance, use aramid fibers. If the cost of carbon fiber decreases, it will be used in big quantity. Regarding the matrix, unsaturated polyester is widely used. For corrosion critical structure, use vinylester. For higher temperature and better strength, use epoxy. Of course, there are many noble materials deserving design engineer's careful attention, see Chapter 2 of Ref(1). Cement matrix may be used in large scale structures if certain required properties are improved.

There are some advises in designing with composites.

1) Consult the composite specialists at the early stage of design, on concepts including material and manufacturing process selection. The mechanical property of the composite depends on both of these.

2) The initial design effort should be concentrated on the most effective shape suited to the properties of the material.

3) Never try to develop a composite structural element based on a design used for another material, such as steel. Many composite structural shapes in the markets are not well suited for the mechanical properties of the composites.

4) A basic knowledge on manufacturing, fabrication, and quality control of composite structural elements must be maintained in order to integrate the design to the manufacturing process. Wilson presents a good article on this subject, Design/Tooling/ Manufacturing Interfaces. The manufacturing and quality control processes are not treated in this book. However, these are available from the References from (10-9) to (10-119)in Ref(1).

5) Reduction of stiffness and strength after long term loading must be considered. Both viscoelasticity and fatigue effects are important for some polymer matrix composites.

6) The maximum operational temperature should be decided. The service temperature of composites in non-aggressive environments should be limited to the materials Tg(glass transition temperature) minus 10°C - 38°C (50° - 100°F) depending on the factor of safety, loading and expected service life.

7) As with any material, the dimensional tolerences, especially due to temperature changes, must be specified.

8) The combined stress effects on the strengths of composites, under expected service environment must be considered, as discussed in Chapter 8 of Ref(1).

9) As discussed in Chapters 8 and 9 of Ref(1) lack of ductility requires detailed, thorongh, local stress analysis. Design details should be made such that the stress concentrations due to notches, sharp corners, and restraints to deformation, etc are eliminated.

3. Proposed Steps of Design Process

As with any material, proper design procedure is very important for successful accomplishment of the project. Each experienced engineer may have his own idea and it is assumed that the reader has the basic knowledge on conventional design method. Figure (1) shows a design process sequence by which it will be explained how the theories involved can be applied for composite design of large scale structures.

After all performance requirements are established (step 2), structural concepts such as structural confignration, material, and manufacturing method, are developed with consideration of economy based on total concept. A steel pipe of certain diameter may be cheaper than composite pipe on market price basis. The welding of one meter diameter steel pipe, however, may take whole day, while connecting certain composite pipes can be done in minutes. If the problems of traffic jams and others are considered, not to mention the maintenence jobs caused by corrosion of steel, the initial cost of pipes may be not imporotant. If the bridge decks and building walls are made of composite panels, the intertia force, in case of an earthquake, is far less than those of conventional materials, and maintenance job will be much easier, because of the light weight of composites. We must consider both short term and long term economy. The structural frames may be made as simple as possible. In fact, the most of the civil and architectural structures can be considered as frames of one dimensional beams and columns. Even two-dimensional plates can be solved as collection of beams (10-146 of Ref 1). Three dimensional shells are often analyzed as collection of two-dimensional plates or one-dimensional frames (10-147 of Ref 1.) If this is done based on advices of an experienced engineer, the result of such simplified analysis is not far off from that of "exact" solution. If too many assumptions are made, obtaining solution may be easy but the result may be too far off. If too few simplification is made, the problem may turn out to be impossible to be solved. One must trade-off between practicality and accuracy. Again, experience can make this gap closer.

With chosen material and manufacturing method, the range of material strengths can be estimated. With this strengths data, the initial dimensions of this frame work can be obtained. One may start by assuming the element is either quasi-isotropic or unidirectional to the structural axis. Experienced engineers can assume even variable sections to obtain good result at an early stage. General guideline is to use quasi-isotropic concept for two-dimensional problems and unidirectional concept for one-dimensional frameworks. This concept is indirectly supported by the recent papers of Verchery et al(Ref #10-210, 211, 212 in Ref 1). The classical mechanics and elasticity theory can be used if the material is quasi-homogenous, i.e., $D^* = A^*$,
where $D^* = (12/h^3)D$ and
$A^* = A/h$
in which A and D are the extensional stiffnesses and bending stiffnesses, respectively, and h is the thickness of the laminate. Verchery reports that the influence of anisotropy on the deflection is always in the range of +10% with reference to the deflection for the isotropic case,except the unidirectional laminate for which the central deflection is about 13% in excess. He reports that the influence of anisotropy on the curvatures is more important than on the deflection, but generally remains small. The concept of using quasi-isotropy is very important because the maximium stress or the maximum strain strength/failure theory involves six equations for each lamina(For 100 laminae,600 equations!!). The engineers are scared of using composite materials from the beginning stage of design. The relation between anisotropy and the critical buckling load, and that of the natural frequency of vibration will be reported separately. The quasi-isotropic stiffnesses of some laminate configurations will be reported separately also. At this stage, tests are performed to obtain the mechanical properties, i.e., E_x, E_y, ν_x, and E_s,

of material chosen.

With this frame work and the material properties, analysis is carried out to obtain the maximum stresses and strains, dynamic responses, and stability conditions (step 5). Then we proceed to step 6 to revise the design, including joints. We may have combined stresses at this stage, and we reinforce the sections to take care of such "new" stresses. With these new sections and frameworks, analysis is carried out again to get "exact" stresses and strains. Tests are made to obtain the strengths of the material by means of loading the test coupons. With the stresses of the frame work and the material strengths, the failure (or strength) criterion, discussed in Chapter 8 of Ref(1), are applied. Either limit or ultimate strengths are used for this purpose. If any section turns out to be too weak, we go back to step 6 to reinforce it. We may do the same in case of over-design also. Otherwise, we go to step 9 to make detail drawing.

With civil and architectural structures, testing prototype is almost impossible. These structures are huge in sizes and, in most cases, a design is different from the other. We have to be careful in design and analysis of both structures and materials. However, the science of composite is well established and we should have good confidence in huge structures made of composite materials, if enough attention is given.

From long history of human civilization, four basic concepts of structures have evolved and developed. These are beam and column, masonry arch, wooden truss, and modern steel truss and frame. These concepts were made possible by available materials and applicable technologies of each age. Modern science and engineering have produced numerous noble materials and technologies, and it is necessary to have a new concept which the author wishes to call the fifth concept of structures. The composite structures belong to this concept and this concept is very much diversified.

The classical four concepts include steel I, WF, T, L, and other sections. Using composite materials for such elements may not be too efficient structurally. However, other reasons such as corrosion, electro-magnetic, and other problems allow the use of composite materials for such sections. Design of such elements will be discussed in the next article.

4. Design and Analysis of Structures of Four Basic Concepts

The first concept, beam-column, is different from the modern beam-column concept, which is often used in framed structures, that belong to the fourth concept. In the first concept, the beam is subjected to bending and shear, and the column is acted on by axial load only. The second concept, even though the Roman arches were subjected to axial loads only, will include the modern arches which are acted on by axial, shear, bending, and even torsion. The third concept, trusses, are handled by considering axial loads, and moments if necessary. The fourth concept includes the modern steel frames and isotropic plates and shells. The isotropci plates and shells are considered as special cases of anisotropic plates and shells, and therefore, will be treatced as the fifth concept.

With above classification, structural elements for all four concepts can be handled by the theories discussed in Chapter 6 of Ref (1). The expressions for the stiffnesses are given in that chapter. With these stiffnesses, the methods of analysis in Chapters 3 and 4 can be used to obtain the forces and moments, with consideration of vibration and buckling problems. Then, the methods of calculating the stresses and strains of structural members made of composite materials, given in Chapter 6, can be used before proceeding to apply the strength theory, given in Chapter 8, with proper joints explained in Chapter 9, to conclude the design.

There are several manufacturers producing standard structural elements. Some of them present design guides. These design methods are essentially same as those of steel structures. It is stongly recommended that the methods for composite materials should be used, that is the stiffnesses, and stresses and strains by Chapter 6, failure criteria by Chapter 8, and joint design by methods given in Chapter 9, in Ref(1).

Depending on the purpose of application and geological location, we may have different codes and specifications. Any engineer must be able to design and construct structures made of composite materials without such codes and specifications, if these are not available. The confidence in his ability and theroies is very important for professional achievement. The large number of, probably almost half of, the structures the author designed and built were executed when no code was available. Some structures were constructed by only a fraction of the cost required by the other conventional design, and these are still sound and good after several decades.

There is one thing which bothers the engineer most when the code is not available. It is the concept of the factor of safety or load factor.

Some manufacturers manuals present the factors of safety. Some of these are too conservative, but given as follows, as a guideline for the independent design work.

The factor of safety FS, is the rate of the ultimate strength to the allowable working stress.

For Columns, FS = 3.0
For Beams,
  Bending : FS = 2.0 (Buckling Considered)
  Shear : FS = 3.0
  Deflection : FS = 1.0
Framed Connection : FS = 4.0

When the codes are not available, the following facts must be considered to determine the F.S.

1) The accuracy of assumed loadings
2) The accuracy of theories and methods used for analysis
3) The low ductility of composites prevents the stress relief at stress concentration areas
4) The stiffness and strength greatly depends on environment condition
5) The influence of loading condition on the ultimate strength must be studied carefully.

For example, a design guide suggests FS as follows.

For static load : FS = minimum 2.0
Fatigue or Repeated Load : FS = minimum 4.0
Impact Load : FS = minimum 4.0

The selection of the factors of safety is ultimately, the responsibility of the designer.

5. Design of Structures of the Fifth Concept

5-1. General

The structural elements belonging to the fifth concept are very much diversified. These elements havd been used intensively by the other branches of engineering profession. Many of civil engineers, including building engineers, however, have had some unjustifiable prejudices against the use of such elements. It is true that the composites in the past were used mostly for low volume, high performance applications with little consideration on cost. With present cost of some materials and manufacturing methods, design plays a vital role on cost of the product. Even with conventional materials, design method can bring the construction cost down profoundly. Some of the experiences of the author are as follows.

1) An elevated expressway with the length of 3.1 Km in Seoul was designed in 1967. New design concepts including composite action (which was not new then), grid analysis considering whole bridge deck and girders, welding and use of high-tension bolts, hybrid structure concept,and others resulted to economical structure. The total steel tonnage used compared with that of conventional design was 30/80 [Ref (10-142) in Ref(1)].

2) A communication and tourist observation tower with the height of 270 meters from the foundation was designed and built in 1970 [(10-143)in Ref(1)]. After thorough analysis and careful study of construction method, it was built by about half of the cost originally estimated.

3) Military structures north of Seoul were designed and built based on entirely new and idependently developed concepts. Several of these structures were built by 3/25 of the initially estimated cost.

All of the structures mentioned above are structurally sound and perform perfectly after two decade's service lives.

Very large portion of civil structures can be analyzed by considering them as frameworks of one dimensional elements. For such structures, the methods presented in Chapters 3 and 4 of Ref(1) are good enough. Composite materials are, generally, strong in tension. When an element is designed based on tension load, it will have thin section which is weak against any loading type other than in-plane on-axis tension load. This requires the section modulus increase by means of employing thin walled structure or sandwich panels. Even the one dimensional element, after the frame is analysed, requires additional study by the methods explained for thin walled sections. The thin panels of such section is weak against the load normal to this panel. The longitudinal stringers are added between transverse diaphragms to take care of such loads. The diaphragms transmit the loads from stringers to the walls of the beam by means of in-plane shear. The problems of thin walled section with longerons (stringers) are extensively discussed in Chapter 3 of Ref(1).

5-2. Quasi-Isotropic Constants

The initial analysis of any composite structural element including the one-dimensional one, may be started by using this concept of quasi-isotropic constants. Every anisotropic material has quasi-isotropic constants derived from the invariants of coordinate transformation. These constants represent the lower bound of each composite performance. Whatever ply orientation is selected for an applied load the laminate performance is at least equal to the quasi-isotropic laminate. These quantities are invariant and are better design parameters than any stiffness component. Tsai (1) gives these parameters as,

$$[Q]^{iso} = \begin{vmatrix} U_1 & U_4 & 0 \\ U_4 & U_1 & 0 \\ 0 & 0 & U_5 \end{vmatrix}$$

where

$$U_1 = \frac{1}{8}(3Q_{xx}+3Q_{yy}+2Q_{xy}+4Q_{ss})$$

$$U_4 = \frac{1}{8}(Q_{xx}+Q_{yy}+6Q_{xy}-4Q_{ss})=U_1-2U_5$$

$$U_5 = \frac{1}{8}(Q_{xx}+Q_{yy}-2Q_{xy}+4Q_{ss})$$

Note that Tsai uses the letter subscripts for on-axis quantities.

$$[S]^{iso} = \begin{vmatrix} U_1/\Delta & -U_4/\Delta & 0 \\ -U_4/\Delta & U_1/\Delta & 0 \\ 0 & 0 & 1/U_5 \end{vmatrix}$$

where $\Delta = U_1^2 - U_4^2$,

and

$$E^{iso} = \Delta/U_1 = (U_1^2 - U_4^2)/U_1 = U_1[1-(\nu^{iso})^2]$$

$$\nu^{iso} = U_4/U_1$$

$$G^{iso} = U_5$$

With these values, the preliminary analysis can be carried-out. The equations and formulas obtained by classical strength of materials textbooks can be used to analyze the behavior of the structure. The orientations of the laminae may be decided according to this result. Then the off-axis quantities are obtained by proper transformation equations. If necessary, we modify the section and calculate stiffnesses for this "new" section to proceed to "refined" analysis.

6. Ultimate Strengths of Laminates

In Chapter 8 of Ref(1), the first-ply-failure (FPF) envolopes are discussed. These can be obtained by direct application of laminate theory with chosen failure criterion. Some conservative engineers may consider this FPF as the criteria of the ultimate strengths of the laminated composites. In fact, the failure envelopes based on intact plies are valid only up to the FPF. As long as we do not go beyond the FPF, which defines the limit of intact plies, we can keep on loading and unloading without having the irreversible effects. A structure may experience an unexpected loading and, if the damage is not serious, it can function as usual so long as the loads are under certain limit.

If load is increased beyond FPF envelope, cracks begin to form within the matrix and at the fiber-matrix interface, parallel to the fibers in unidirectional plies. As the load keeps on increase, more cracks are formed until a saturation level is reached just before the ultimate failure of the laminate. As long as the ply is still embedded in the laminate, it will continue to contribute to the stiffness of the laminate. Tsai proposes to replace the cracked plies with a continuum of lower stiffness and to apply the conventional stress anlysis. According to his experiments, if the matrix reduction is 40%, the transverse stiffness reduction is 55%, the shear modulus by 45%. Conventional arbitrary practice of setting both transverse and shear moduli to nearly zero is not recommended. It is assumed that the reduction of the major Poisson's ratio is by the same percentage as that of matrix modulus.

It is necessary to calculate only the first and the last ply failures. If the applied load is increased monotonically, the stress-strain curve moves from the origin to the FPF point on the "intact" line, then deviate to the LPF point on the "totally degraded" line. The "jump" from the "intact" to the "degraded" stress-strain curves is not as big as shown in Figure(2). For practical laminates, the loss of laminate stiffness due to matrix degradution is less than 10%. The FPF and LPF points appear to be on the same stress-strain curve (1).

The netting analysis for the pressure vessel subjected to internal pressure is not a theory. It is derived from consideration of the equilibrium of a balanced angle ply construction and does not satisfy the strain compatibility. It does not depend on the stress-strain relationship of the material. The notion that the fiber carries all load in the uniaxial tension of a unidirectional composite can not be extended to the off-axis plies without laminate plate theory.

The LPF is usually greater than FPF in the tension-tension and tension-shear domains. LPF may be less than FPF is compression-compression and tension-compression domains, i.e., FPF is the ultimate strength. If the loading is alternate loading and unloading, and reloading, or fatigue loading, the failure modes become complicated.

When a balanced angle ply laminate is subject to combination of normal stresses with no shear, or when a laminate is subjected to hydrostatic tension or compression, the strains of both LPF and FPF are equal for all fiber orientations, and laminate will have simultaneous failure. This situation, however, does not mean the optimum laminate configuration.

The mode of failure depends on the loading history.

Tsai recommends the use of matrix degradation model, Figure(2), as a means of predicting the ultimate load of laminated composites,(1). The failure envelopes he presents are based on

the stress interaction term = -0.5
the matrix degradation = 0.3
the safety factor = 1.5

The ultimate strength is defined as the larger of the FPF and LPF, see Figure(3).

The safety margin(safety factor) is defined as the ratio of the load carrying capacity of a structure to the limit load. For design of composite materials this margin is often 1.5. The limit strength is defined as the strength induced by the maximum load which a structure is expected to encounter during its lifetime.

Tsai defines :

The ultimate envelope,
"Ultimate" = MAX (FPF, LPF)
or the larger of FPF and LPF forms the ultimate envelope.
The ultimate based limit envelope,
"limit* " = ultimate / FS
where FS = safety factor or safety margin.
The design limit envelope,
"limit" = MIN(FPF, ultimate)
There are two safety margin relations,
safety margin = "ultimate" / "limit* "
safety margin $\leq$ "ultimate" / "limit"

In case of a filament wound pressure vessel, leakage starts at FPF. If the leakage is prevented by seal liner, the burst pressure occurs when fiber fails. The fiber strength of this vessel is fully utlized beyond the FPF envelope.

7. Design of Structures of the Fifth Concept.

The long fiber reinforced composites generally have high specific strength and stiffness. The maximum structural efficiency can be obtained when such elements are under tension and the shape of the section is thin. This results to stability problem if the loading is other than tension. The cross section of an element made of composite materials, except when such element is always in tension, will have shapes such that the momement inertia of the section is increased. Some of the structural shapes belonging to the fifth concept are, tension members including three - dimensional ones, arches, curved girders, flexural members including sandwiches, shells and folded plates. Extensive and detailed discussion are given in Chapter 10 of Ref(1).

8. Conclusion

Designing structures with composite materials gives the engineering wide variety of choices for opitimum designs and flexibility for overall concepts. However, lack of design principles on connections, strength/failure theories, design concepts, and others discourages the engineers from applying composite for primary construction structures. The author wrote a book to provide for the engineers general guidelines to handle such problems. This paper is an except of the Chapter 10 of this book. It is hoped that this paper may help structural engineers to find proper direction, to study the composite structural mechanics and to obtain right concept on composite design.

Reference

1. Kim, D.H., Composite Structures for Civil and Architectural Engineers, Elsevier Science Publisher Ltd., to be published December, 1991.

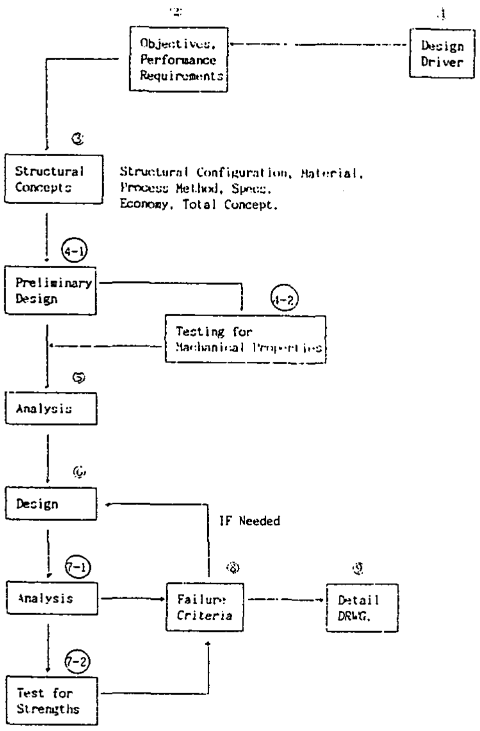

Figure 1 . Typical Design Process

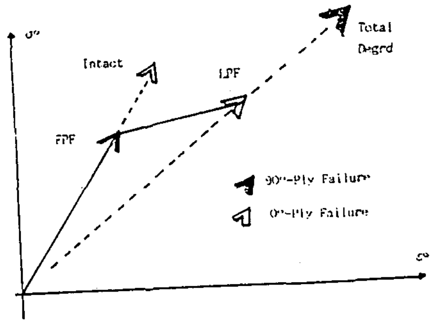

Figure 2 Simplified Prediction of the Last-Ply-Failure is Based on the Laminate with Totally Degraded Plies.

(Courtesy of Think Composite)

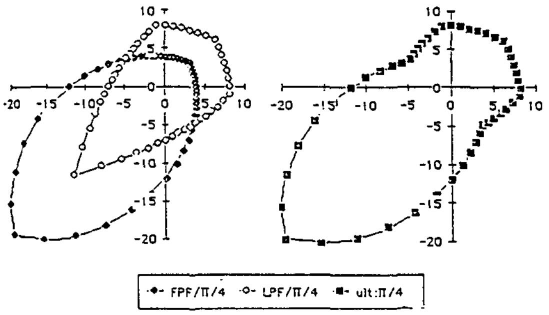

Figure 3. (Courtesy of Think Composite)