건설에서의 복합재료
-설계된 구조물을 사용한 건설 II-

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COMPOSITES IN CONSTRUCTION
- CONSTRUCTION WITH DESIGNED STRUCTURES II -

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Key Words : size/scale effects, failure analysis, natural frequency.

ABSTRACT

Almost all buildings/infrastructures made of composite materials are fabricated without proper design. Unlike airplane or automobile parts, prototype test is impossible. One cannot destroy 10 story buildings or 100-meter long bridges. People try to build 100-story buildings or several thousand meter long bridges. In order to realize "composites in construction", the following subjects must be studied in detail, for his design: Concept optimization, Simple method of analysis, Folded plate theory, Size effects in failure, and Critical frequency. Unlike the design procedure with conventional materials, his design should include material design, selection of manufacturing methods, and quality control methods, in addition to the fabrication method.

1. Introduction

Buildings/bridges by the reinforced concrete/steel are three-dimensional structures made of composite materials, such as cement, steel bars, etc.

However, the engineers can design/analyze such structures by considering them made of one-dimensional beams/columns. But, they are protected by codes and specifications. Almost all buildings/infrastructures made of composite materials are fabricated without proper design. Unlike airplane or automobile parts, prototype test is impossible. In order to realize "composites in construction", the following subjects must be studied in detail.

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2. Size/Scale Effects In the Failure of Composite Structures

Size effects influence the material properties of quasi-brittle materials (e.g. concrete and rocks). In case of any material, the larger the volume the greater is the probability of larger flaws. More recently, the mechanics of materials were studied at various scales ranging from atomic scale to microns to large macro or structural behavior. It has been known that linear elastic fracture mechanics (LEFM) applied to lavoratory size quasi-brittle materials underestimates fracture toughness.

Classical LEFM technique may underestimate the true toughness of certain quasi-brittle materials such as geomaterials by as much as an order of magnitude, especially for those with large scale heterogeneities, and using typical laboratory size specimens.

The question remains as to how laboratory tests could produce a toughness value closer to the in-situ true fracture toughness. We can either build a huge laboratory and test huge specimens: or we can abandon the concept of LEFM.

In composite structures reasonable theory of size/scale effects on the failure mechanism is still lacking. Reduction in fiber strength is experienced when the size of the structures fiber bundle increases.

An efficient method to characterize the relationship between strength distribution and size in composites is not complete yet. It has been known that large composites are generally weaker than small composites. There could be several reasons for such phenomenon. One of the most important causes is the scale effect in brittle reinforcing fibers. Brittle fibers are generally strong and uniform in diameter but have the possibility of containing flaws with different strength. A longer fiber may have more of such possibility than a short fiber.

Based on the experience of a composite manufacturing specialist, the rate of decrease of tensile strength of glass fibers used for filament wound tubes as the mass of fibers increases is as shown in Fig. 1.From the test result reported by Crasto and Kim [2], an approximate relation between 90° tensile strength reduction rate, Y, and the volume (proportional to the mass), for the unidirectional composites of AS4/3501-6, can be expressed as Fig.2. Unless there is the test result for the same matrix to be used, this equation for epoxy can be used to estimate the rate of the decrease of 90° tensile strength.

For each of the constituent materials, both fibers and matrices, the rates of decrease of strengths, X, X', Y, Y', and S, as the mass increases, must be obtained in the future. The manufacturing method and other possible factors also have to be considered.

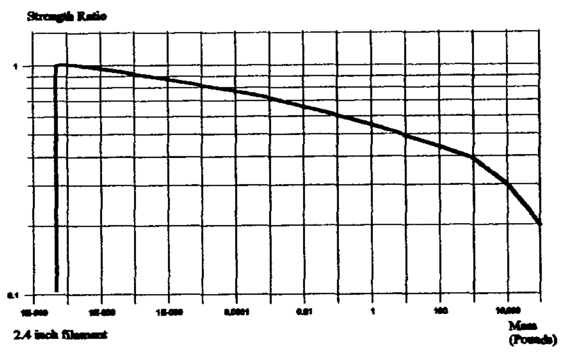

Fig. 1 Rate of decrease of glass fiber tensile strength based on mass

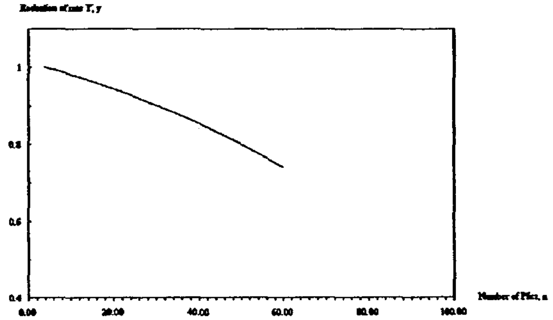

Fig. 2 Tensile strength reduction rate of epoxy matrix based on mass

Any strength theory can be used with "reduced" strength as given above.

Comments on Both Strength and Strain Criteria

Both the maximum stress and maximum strain criteria assume no interactions among the possible five modes. Since the Poisson's ratio is not zero, there is always coupling between the normal components, and this leads to disagreement between these two criteria regarding the magnitude of the load and the mode for the failure.

The result of two criteria agrees only on the shear plane and along the four lines of constant failures due to uniaxial stresses. Just as the deformation of a body is always coupled by the nonzero Poisson's ratio, failure of a body is also coupled. Because the micromechanics of failure is highly coupled, we should not extend the simple failure modes based on maximum stress or maximum strain components to fiber, matrix, and interfacial failure modes.

Recommended Strength-Failure Analysis Procedure

With available information at present, the following strength-failure analysis procedure is recommended for glass fiber reinforced composites with epoxy matrix.

1. Obtain reduced X by Fig. 1.
2. Assume the scale effect is the same for both tension and compression. (This assumption may be corrected when detailed research result is available).
3. Obtain Y=Y(Coupon) x by Fig. 2.
4. Obtain Y'=Y'(Coupon) x by Fig. 2.

   (Again, this may be corrected when accurate study result is available).
5. Assume S=S (Coupon).
6. Use Tsai-Wu failure criteria for stress space. Since the rates of decrease of the moduii are not known, use of the criteria for strain space is complicated.

3. Vibration Analysis

The problem of deteriorated highway concrete slab is very serious all over the world. Before making any decision on repair work, reliable non-destructive evaluation is necessary. One of the dependable methods is to evaluate the in-situ stiffness of the slab by means of obtaining the natural frequency. By comparing the in-situ stiffness with the one obtained at the design stage, the degree of damage can be estimated rather accurately.

However, if the plate has boundary condition other than simple supported, non-uniform cross section, both material and geometry, and non-uniform loading, obtaining a reliable solution is very difficult. The basic concept of the Rayleigh method, the most popular analytical method for vibration analysis of a single degree of freedom system, is the principle of conservation of energy ; the energy in a free vibrating system must remain constant if no damping forces act to absorb it. In case of a beam, which has an infinite number of degrees of freedom, it is necessary to assume a shape function in order to reduce the beam to a single degree of freedom system. The frequency of vibration can be found by equating the maximum strain energy developed during the motion to the maximum kinetic energy. This method, however yields the solution either equal to or larger than the real one. For a complex beam, assuming a correct shape function is not possible. In such cases, the solution obtained is larger than the real one.

Recall that Rayleigh's quotient ≥ 1[1, pp 189~191].

Several structural elements such as the floor slabs of a factory or a building and others may be subject to point mass/masses in addition to its own masses. Design engineers need to calculate the natural frequencies of such elements but obtaining exact solution to such problems is very much difficult. Pretlove[3] reported a method of analysis of beams with attached masses using the concept of effective mass. This method, however, is useful only for certain simple types of beams. Such problems can be easily solved by presented method. The effect of the amount and the location of the concentrated mass on the natural frequency can be easily solved.

A simple but exact method of calculating the natural frequency corresponding to the first mode of vibration of beam and tower structures with irregular cross-sections and attatched mass/masses was developed and reported by Duk-Hyun Kim in 1974 [4]. Recently, this method was extended to two dimensional problems including composite laminates, and has been applied to composite plates with various boundary conditions with/without shear deformation effects and reported at several international conferences including the Eighth Structures Congress[5] and Fourth materials congress[6] of American Society of Civil Engineers.

Method of Analysis

A natural frequency of a structure is the frequency under which the deflected mode shape corresponding to this frequency begins to diverge under the resonance condition. From the deflection caused by the free vibration, the force required to make this deflection can be found, and from this force, resulting deflection can be obtained. If the mode shape as determined by the series of this process is sufficiently accurate, then the relative deflections(maximum) of both the converged and the previous one should remain unchanged under the inertia force related with this natural frequency. Vibration of a structure is a harmonic motion and the amplitude may contain a part expressed by a trigonometric function. Considering only the first mode as a start, the deflection shape of a structural member can be expressed as

$$w = W(x, y)F(t) = W(x, y)\sin \omega t \quad (1)$$

where W : the maximum amplitude
ω : the critical circular frequency of vibration
t : time.

By Newton's Law, the dynamic force of the vibrating mass, m, is

$$F = m\frac{\partial^2 w}{\partial t^2} . \quad (2)$$

Substituting Eqn 1 into this,

$$F = -m(\omega)^2 W \sin \omega t. \quad (3)$$

In this expression, ω and W are unknowns. In order to obtain the natural circular frequency, ω , the following process is taken. The magnitudes of the maximum deflection at a certain number of points are arbitrarily given as

$$w(i, j)(1) = W(i, j)(1) \quad (4)$$

where (i, j) denotes the point under consideration. This is absolutely arbitrary but educated guessing is good for accelerating convergence. The dynamic force corresponding to this(maximum)amplitude is

$$F(i, j)(1) = m(i, j)[\omega(i, j)(1)]^2 w(i, j)(1). \quad (5)$$

The "new" deflection caused by this force is a function of F and can be expressed as

$$w(i, j)(2) = f\{m(k,l)[\omega(i, j)(1)]^2 w(k,l)(1)\}$$
$$= \sum^{k,l} \Delta(i, j, k, l)\{m(k,l)[\omega(i, j)(1)]^2 w(k,l)(1)\} \quad (6)$$

where Δ is the deflection influence surface. The relative(maximum) deflections at each point under consideration of a structural member under resonance condition, $w(i,j)(1)$ and $w(i,j)(2)$, have to remain unchanged and the following condition has to be held :

$$w(i,j)(1)/w(i,j)=1. \quad (7)$$

From this equation, $\omega(i,j)(1)$ at each point of (i,j) can be obtained, but they are not equal in most cases. Since the natural frequency of a structural member has to be equal at all points of the member, i.e., $\omega(i,j)$ should be equal for all (i,j), this step is repeated until sufficient equal magnitude of $\omega(i,j)$ is obtained at all (i,j) points. However, in most cases, the difference between the maximum and the minimum values of $\omega(i,j)$ obtained by the first cycle of calculation is sufficiently negligible for engineering purposes. The accuracy can be improved by simply taking the average of the maximum and the minimum, or by taking the value of $\omega(i,j)$ where the deflection is the maximum. For the second cycle, $w(i,j)(2)$ in

$$w(i,j)(3)=f\{m(i,j)[\omega(i,j)(2)]^2 w(i,j)(2)\}, \quad (8)$$

the absolute numerics of $w(i,j)(2)$ can be used for convenience.

In case of a structural member with irregular section including composite one, and non-uniformly distributed mass, regardless of the boundary conditions, it is convenient to consider the member as divided by finite number of elements[4]. The accuracy of the result is proportional to the accuracy of the deflection calculation.

4. Conclusion

Unlike airplane or automobile parts, prototype tests for buildings and bridges are impossible. Nevertheless, almost all buildings/infrastructures made of composite materials are fabricated without proper design. Design/analysis of such structure is simply too difficult for most of the engineers. In this paper, size/scale effects in failure of composite material structure are briefly explained. The effect of size/scale may be very serious. The numerical example in [4] shows that the safety factor is between 5.459 and 1.5699.

A simpler but exact method of vibration analysis of structural elements with irregular loadings and sections is also given herein.

Reference

(1) Duk-Hyun Kim, Composite Structures for Civil and Architectural Engineering, E & FN SPON, Chapman & Hall, London, 1995.

(2) A.S. Crasto and R.Y. Kim, "The Influence of Specimum Volume on Matrix Dominated Composite Strength", Proc. 38th SAMPE Symposium, 1993.

(3) A.J. Pretlove, "A Simple and Accurate Method for Calculating the Fundamental Natural Frequencies of Beams with Attached Masses", International J. of Mechanical Enfineering Education, Vol. 15, No.4, Ellis Horwood LTD., England, 1987, pp257~266.

(4) Duk-Hyun Kim, et al, "The Importance of Size/Scale Effects in the Failure of Composite Structures", Proc. 4th Japan International SAMPE Symposium, 1995,pp837~843.

(5) Duk-Hyun Kim, "A Method of Vibration Analysis of Irregularly Shaped Structural Members", Proceedings, International Symposium on Engineering Problems in Creating Coastal Industrial Sites, Seoul, Korea, October,1974.

(6) Duk-Hyun Kim, et al,. (1990), "Vibration Analysis of Irregularly Shaped Composite Structural Members-For Higher Modes", Proc. 8th Structural Congress, American Society of Civil Engineers, Baltimore, MD, U.S.A.,1990

(7) Duk-Hyun Kim, "Vibration Analysis of Special Orthotropic Plate with Variable Cross-Section and with a Pair of Opposite Edges Simple Supported and the Other Pair of Opposite Edges Free", American Society of Civil Engineers, Washington DC, November, 1996.