Composite for building and bridge construction –
Modeling of mechanical behavior of structural
element using mixed steel composite reinforced
concrete or mixed composite prestressed concrete
P. Hamelin
Laboratoire Mécanique Matériaux – IUT A Génie Civil -
Université Claude Bernard, Lyon I – 43 Boulevard du 11
Novembre 1918, 69622 Villeurbanne Cedex, France
E-mail: hamelin@iutal2m.univ-lyon1.fr

Abstract

After an examination of the different applications cases of composite materials in
civil engineering, we consider the different design methods of reinforced-composite
concrete and prestressed-composite concrete beams: specific finite elements or non-
linear analytical methods.
We particularly examine the main problems which concern modeling of interface
between concrete and composite sheet. We show that the perfect evaluation of non-
linear behavior law of each component (concrete, steel rebars, interface) is very
important for a good prediction of beam deflection.
Comparison between finite element method and usual design method defined by ACI
or CEB code are satisfying. It is obvious that for basic cases, the non-linear method
is enough precise. Numerical method and mixed finite element are particularly
interesting for modeling specific structures as plate or shell.

Introduction

The composite materials associating fibers of different nature (glass, carbon,
aramid, polyester, polyethylene...) with organic matrix (epoxy, polyester,
polyurethane...) or with mineral matrix (Portland cement, magnesian
cement...) are certainly the XXIst century construction materials insofar as their specific properties (ratio between mechanical characteristics and density or natural weight), insofar as their moulding and forming capacities, insofar as their combined properties (multi-properties: mechanical - thermal - acoustic - corrosion...) allow to conceive and make more efficient and more durable structures than the ones with traditional materials (steel, concrete, reinforced concrete, wood...).

The main families of composites and their applications in the field of civil applications fall into the three following categories: soft composites and tensile architecture and composites tendons for industrial applications as suspension bridge (table 1), stiff composites and high performance structures (table 2), fibers-cement composites for the construction industry.

Table 1: "Soft" composites

Independently of the usual characterization problems taking into account the anisotropic and orthotropic characteristics of these materials, their material non-linearity under uni-axial and multi-axial solicitation, their thermo-rheological behavior and more particularly their creeping and relaxation functions are very important to design these structures. In particular, with respect to the failure initiation mechanisms in the vicinity of geometrical singularities and edge effects.
One can find the same problem in the case of cables for suspension bridges or for reinforced concrete constructions with post-tensioning. The performance of these construction processes is directly dependent on the anchorage system where it is necessary to minimize the effects of stress concentration and the loss of tension loads due to environmental conditions.

In the case of "stiff" composites (table 2) associating thermosets and glass, aramide or carbon fibers, the design problem is exactly the same as the one met for the aeronautical and automotive applications. Industrial applications use manufactured half-products such as pultruded profiles to create structures with a design similar to metallic ones. In this case, the critical problems essentially concern the joint and buckling stability.

Composite materials have been considerably developed during the last few years, to ensure repair, reinforcement and protection of existing civil engineering structures (reinforced concrete, prestressed concrete, metallic frames). The wrapping of bridge piles, the beam reinforcement (figure 1) towards traction or shear is particularly efficient in the case of carbon epoxy composite. The design codes for traditional materials (ACI, Eurocode) might change, in order to take into account these new materials. However some difficulties concern some realistic adhesion characteristics between concrete and composite and specific failure modes particularly catastrophic in the case of composites.
The design of works that includes composite materials must take into account the interaction material - structure described in the table 4. In this table, it is possible to understand that structure optimization can be made by new formulations selection (new matrix, new reinforcements, new stacking sequences, new techniques of manufacturing) and not necessarily by the geometrical structure thickness modification that corresponds to the usual methods of design in the case of isotropic homogeneous structures.

As a consequence, it is necessary to know exactly how to define the load conditions of constructions (load conditions, environmental conditions, expected lifetime...).
General data for infrastructures design

The load conditions of structures are taking into account the own weight of the structure, the service loads, the extreme loads. The low density of composite materials is an asset in order to minimize the own weight of the construction. Moreover it is known that their use influence the design of tensile structures (tensile architecture, cable stayed bridges...).

The service loads are generally standardized, hereby using values corresponding to the nature of the building or the bridge. It is important to notice that the extreme solicitations (impact solicitation, seisms, and explosions) are taken into account in the traditional design rules by a static load redefinition. If this approach is not a significant problem, in the case of traditional materials, it is necessary to take into consideration multiplication coefficients that take include the sensitivity, the variation of materials behavior laws with respect to the loading conditions.

Likewise, in the case of extreme environmental solicitations (temperature, hygrometry, corrosion...), it is imperative to take into account the variations of resistance, of ultime extensional modulus or damage variables specific for composite materials.

Consequently, for numerous applications, it is possible to transfer acquired knowledge on the aging of polymers, composites used in the transportation field (aeronautic, automotive) to the civil engineering field. Nevertheless, we can notice that the accelerated aging methods, the prevision methods (time-temperature-dependence) are confronted to estimates of lifetime of 10 years, 20 years, 50 years... So, the retrofitting and repair problems are more and more important when taking into consideration combined solicitations (mechanical - thermal - hygrometric) and are more and more difficult to model. In view of effects of composite materials heterogeneity analyzed at different scale levels: (fig.2)

1. - microscopic scale: fiber - matrix - interface,
2. - mesoscopic scale: internal structure of stacking or weaving,
3. - macroscopic scale: multi-materials, mixed structures...

it is necessary to conceive analysis or design codes that integrate the physical phenomena which occur at each level.
We essentially develop two different approaches for the design of such structures (usual or finite elements or specific formulation for modeling interface behavior and modified design recommendations following prescription of CEB or ACI code).

Repairing techniques using carbon-epoxy laminates applied on lateral sides of concrete or prestressed concrete beam allow to modify tensile and shear properties of concrete. They also influence cracking mechanism and protect concrete against corrosion and environmental effects.
Consequently, the main parameters that influence the structural behavior of multimaterial composite beams are the following:
- interface properties between composite and concrete,
- behavior laws and particularly concrete damage level in tensile zones and transition zones between metallic bars and composite sheets.

**Numerical methods: finite element method**

Modeling composite-concrete beam or composite-steel beam is particularly difficult along interface zone. Usually, it is possible to analyze structural behavior meshing the beam by classical displacement elements (figure 4). The validity limit of these methods and their precision degree are directly dependent on the meshing quality, on the behavior law that is taken into consideration and on the hypotheses of small or large displacement.

**Figure 4: Tensile-shear test of mixed concrete-composite specimen**

**Figure 5: Shear-stress distribution**

In the case of non-linear behavior of a beam in traction induced by concrete cracking, rebars slipping, composite peeling off... It is very difficult to predict, to calculate the relation between external bending moment and curvature.
Specific finite elements for interface analysis between composite and concrete

Usual formulations of finite displacement elements assume kinematic continuity at interface level but are not very efficient regarding static variables along boundaries, along interface.

![Image showing material separation and displacement continuity](image)

**Figure 7: Kinematic continuity of displacement (a); forces equilibrium (b)**
Basic equations along the interface: $\ddot{u}(1) = \ddot{u}(2)$ on $\Gamma_{12}$

Equilibrium of surface load: $\vec{T}(1) + \vec{T}(2) = \vec{0}$ on $\Gamma_{12}$

Stress vector along the interface: $\sigma_{ij}(1)n_j(1) + \sigma_{ij}(2)n_j(2) = 0$ on $\Gamma_{12}$

Mixed methods combining two kinds of variables (displacement, forces) are able to model mechanical behavior along the interface. Using Reissner principle [1950], different authors like Pian [1964], Washizu [1975] and Verchery [1973, 1987] have developed many others formulations.

Variational Reissner principle corresponds to the following relation where $S_{ijkl}$ is the material compliance.

$$R(\sigma_{ij}, u_i) = - \int_V \left\{ \sigma_{ij}, u_i + 1/2 \sigma_{ij} S_{ijkl} \sigma_{kl} \right\} dV + \int_{\Gamma_{ij}} (\sigma_{ij} n_j \vec{T}_i) u_i dS_{ij}$$

Other kinds of static variables

To avoid difficulties induced by the excessive continuity of stress tensor components, we suggest to choose other static variables, for example stress vector components $\sigma_{ij}n_j$.

To solve the problem of the multi-value stress vector at the element nodes, Verchery [1987] proposes to "relocate" the problem and to consider stress vector along the element side. It is also possible to minimize the number of unknown variable at each node. This method corresponds to the "elimination technique" developed by Aivazzadeh & al. [1986] where specific behavior law and local equilibrium conditions are used. For instance (figure 8), we introduce Noune, Courtade [1997] a friction Coulomb law along a triangular element side that can be used to model interface behavior between composite plate and concrete when displacement is not perfectly satisfying.
Numerical modeling combining different elements

The main difficulty for a perfect description of the mechanical behavior of the beam depends on the fact that damage mechanisms are numerous: concrete cracking, rebars slipping, reinforcement peeling off, steel yielding. These various phenomena appear at different times and their effects can be combined during the different loading phases. Their development can be localized or uniformly distributed in the whole volume. In recent contributions, Limam [1998] shows (figure 9) that it is possible to describe the mechanical behavior of such structures combining different types of elements (volumic, bars, beam, interface, cracking) and to take into account different behavior laws and failure criteria for each material.
Validity of such methods implies perfect identification of the main parameters that influence behavior law and imply a reposition of numerical modeling in confrontation with experimental results.

**Non-linear methods using ACI, CEB code principles**

Equilibrium of a steel concrete beam or a prestressed concrete beam can be analyzed by load and moment equilibrium equation in a given area (figure 12). We propose a general formulation in the case of composed flexion and its simplification for elementary flexion.

![Diagram of prestressed concrete design method](image-url)
In a first approach, the behavior laws taken into consideration are the following:

CONCRETE IN COMPRESSION
\[ \sigma_b = f_{cd} \left( k \epsilon + \left(k' - 1\right)\epsilon^2 \right) \]

CONCRETE IN TENSION
Linear elastic with post strength

LONGITUDINAL STEEL
Elastic-plastic with hardening

COMPOSITE SHEET
Linear elastic until failure

The following chart of non-linear method has been established by Varastehpour, Nasseri, Hamelin [1997]. First of all, composite characteristics are introduced from evaluation of global equivalent elastic constant (engineer constants). After solving the different equations, the force applied to the composite plate is distributed in the thickness of the material following classical laminated theory. The software developed by L2M Laboratoire Mécanique Matériaux can take into account properties variations and essentially slipping effect along the interface concrete-composite established from experimental test as direct shear test measurement (figure 14).

General equations for beam equilibrium:
\[ \Sigma F_x = 0 \quad \Sigma M = 0 \]
\[ F_b + F_a + F_c + N = 0 \quad M = M_b + M_a + M_c + M_N \]
\[ F_b = \int \sigma_b \, dA_b \quad M_b = \int \sigma_b \, Y \, dA_b \]
\[ N = F_{p2} + F_{c2} \]
The major interest of this design method is a double one: on one hand, we use the classical design principles of steel reinforced concrete and prestressed concrete structures corresponding to construction codes, on the other hand the iterative non-linear design method is adapted to model the fatigue and creep behavior of structures and to take into account the interface behavior law.

**Conclusion**

Whatever the used design method, it is necessary to have at disposal behavior laws valid for each material. The precision level of each design method is directly dependent on the knowledge of concrete damage level and on polymer thermorheological properties. The fact that the composites are characterized by their macroscopic properties is not so bad insofar as the failure mechanisms of the more efficient reinforcement systems are located in the concrete in tension, not in the composite and not in the composite-concrete interface.
Bibliography


