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**AN EXPERIMENTAL STUDY FOR
CONSTRUCTION OF COMPOSITE
REINFORCED STRUCTURE OF STEEL AND
CONCRETE**

An Experimental Study for Construction of Composite Reinforced Structure of Steel and Concrete

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Abstract – Traditionally "steel structures" and "concrete structures" formed more or less two different worlds in structural engineering. Fortunately this situation is changing rapidly. It is now recognised that each of the two materials have advantages and disadvantages and that often an optimal solution is found by combining both materials. This may be a combination of steel and concrete in an element as is the case in "Composite steel-concrete construction" or the combined use of concrete elements and steel elements in "Mixed construction". For the design of composite steel-concrete elements specific design standards have been developed. However for "Mixed construction" a combined use of steel design standards and concrete design standards is necessary. It is important that the design rules for the two materials are consistent, especially for those components connecting both materials. However, in the past the design standards and recommendations for concrete and steel have been developed separately. So evidently at this moment there are considerable differences in design assumptions and treatment of various aspects. In the paper design methods for connections between structural steel and concrete will be discussed. The methods will be illustrated for column bases, being the most frequently used type of connection between steel and concrete, though the information can also be used for related types of connections.

The composite action in members built up of different materials results in savings in construction cost. These savings can be further advanced by employing optimization techniques in the design of composite members. This paper presents an algorithm model for the cost optimization of composite beams based on the specifications of the SR EN 1994-1-1/2006: Design of composite steel and concrete structures.

INTRODUCTION

In the past for the design of a building the choice was normally between a concrete structure and a steel structure. Looking at recent practice there is an evident tendency that designers also consider the combined use of concrete and steel in the form of composite or mixed structures as a serious alternative. Use of composite elements in the form of composite beams, composite columns and composite slabs is already common practice in many countries.

Applications are supported by accepted Standards or Recommendations as for example the European Standard: EN 1994-Eurocode 4. However, this supporting material is not available for mixed constructions where (reinforced or prestressed) concrete elements and structural steel elements are used in combination. The elements itself are covered by the respective design standards for concrete and steel. But in many cases the joints where the elements meet form a black spot as far as Design Standards

and information is concerned. So the designer has to develop design models based on a creative interpretation of methods and rules in use for concrete and steel. It is of course a complication when these design methods for the different materials are not consistent. In the past the Design Standards and Recommendations for concrete and steel have been developed separately. So evidently at this moment there are still considerable differences in design assumptions and treatment of various aspects.

The design of structures for buildings and bridges is mainly concerned with the provision and support of load-bearing horizontal surfaces. Except in long-span bridges, these floors or decks are usually made of reinforced concrete, for no other material has a better combination of low cost, high strength, and resistance to corrosion, abrasion, and fire. The economical span for a reinforced concrete slab is little more than that at which its thickness becomes just sufficient to resist the point loads to which it may be subjected or, in

buildings, to provide the sound insulation required. For spans of more than a few metres it is cheaper to support the slab on beams or walls than to thicken it. When the beams are also of concrete, the monolithic nature of the construction makes it possible for a substantial breadth of slab to act as the top flange of the beam that supports it.

At spans of more than about 10 m, and particularly where the susceptibility of steel to damage by fire is not a problem, as for example in bridges and multi-storey car parks, steel beams become cheaper than concrete beams. It used to be customary to design the steelwork to carry the whole weight of the concrete slab and its loading; but by about 1950 the development of shear connectors had made it practicable to connect the slab to the beam, and so to obtain the T-beam action that had long been used in concrete construction. The term 'composite beam' as used in this study refers to this type of structure.

The degree of fire protection that must be provided is another factor that influences the choice between concrete, composite and steel structures, and here concrete has an advantage. Little or no fire protection is required for open multi-storey car parks, a moderate amount for office blocks, and most of all for warehouses and public buildings. Many methods have been developed for providing steelwork with fire protection. Design against fire and the prediction of resistance to fire is known as fire engineering. There are relevant codes of practice, including a draft European code for composite structures. Full or partial encasement in concrete is an economical method for steel columns, since the casing makes the columns much stronger. Full encasement of steel beams, once common, is now more expensive than the use of lightweight non-structural materials.

For reinforced concrete structures, because of the high alkalinity of the pore solution in the concrete, and the barrier provided by the cover concrete against the aggressive species from outside environment, the reinforcement has been believed to be "non-corrodable", i.e. the corrosion rate of the steel reinforcement has been believed to be too slow to be of concern.

However, with passage of time, some cover concretes would not be able to provide good protection to the reinforcement due to the degradation of concrete and the ingress of corrosive species from environment. Thousands of prematurely damaged concrete structures have been found to be associated with the corrosion of reinforcement. It has been recognised that the concrete can not always be a non-corrosive medium to protect steel from corroding.

Concrete is a very versatile material with its own special properties. It provides a specific environment for the steel inside. Corrosion of steel in such a medium would certainly involve particular processes different from those in other natural environments,

such as, sea water, soil, and atmosphere, etc. Many issues pertaining to the corrosion of steel in such a medium are unsolved or still unfamiliar to corrosion scientists and engineers, and need to be investigated. Also because concrete is quite different from the traditional aqueous corrosion media, some theories and techniques used in the traditional corrosion field may not be directly applicable in the corrosion of reinforced concrete.

Reinforced concrete structures are usually very large. Different parts of a structure could be exposed to different environments, so the same steel rebar in a structure may be subjected to different types of corrosion attacks and various extents of corrosion damage.

CORROSION PROCESSES OF STEEL IN CONCRETE

It was previously believed that the cover concrete could protect the embedded steel reinforcement from corrosion, and as a consequence, reinforced concrete structures were considered to be highly resistant to corrosion. However, practically, reinforced concrete structures usually do not perform so well, and their service lives are sometimes much shorter than what they were designed for. The steel in concrete is always prone to corrosion attack, and a reasonable explanation for the premature damage to the reinforced concrete structure is that the cover concrete is not free of defects.

Microstructural Defects in Concrete - Concrete acts as a special medium for corrosion reactions, and plays an important role in the corrosion processes of the steel in concrete. Particularly, some defects in concrete provide the essential causes for the initiation of corrosion of steel in concrete. Even though a full discussion of such defects is beyond the scope of the review, a brief account of some types of the defects related to corrosion processes is necessary to the understanding of corrosion of steel in concrete.

Firstly, micro-cracking is one of the most important defects in concrete that would be responsible for serious corrosion attack of steel in concrete, greatly shortening the service life of reinforced concrete structures. The cracking in concrete usually provides a short-cut for the ingress of corrosive species from environment into the concrete. The aggressive species could change the chemical properties of concrete seating a more aggressive environment in the vicinity of the reinforcement. Cracks in concrete could be formed by various mechanisms. They could be produced due to bleeding effects, rapid drying of exposed surface of wet concrete, temperature difference in the core and surface of a freshly cast concrete element, shrinkage of hardened concrete, freeze/thaw cycles and external seasonal temperature variation, etc.

Secondly, the porous nature of conventional concrete means that the corrosion of steel is unavoidable in concrete. To some extent, the pores in concrete have a similar effect as the cracks. Through the pores, detrimental species can penetrate into the cover concrete, making the concrete pore solution more corrosive to the reinforcement, and finally initiating the corrosion of the reinforcement. The penetration of detrimental species through the pores is relatively slow compared with those via cracks, but sooner or later, this will lead to the corrosion of steel rebars and damage to the reinforced concrete structure. Normally, a hardened concrete contains different sizes of pores. The pores can exist in and between the hydrated, gel-like phase (largely calcium silicate hydrate, CSH). The pore space includes gel pores and capillaries as well as at the interface between the cement paste and aggregates. Some pores are connected, while some are not. Some are relatively large which would allow the flow of solutions, and some are so fine that only a very small amount of moisture could be absorbed on their surface. All these pores could play important roles in the corrosion of reinforcement.

Lastly, the heterogeneity of concrete further accelerates the corrosion of steel in concrete. It can directly lead to different electrochemical activities of steel in different sections in a concrete structure, resulting in non-uniform corrosion, an even worse corrosion damage of steel than the uniform corrosion. Unfortunately, the heterogeneity is unavoidable in field structures. At a micro-scale, the non-uniform distribution of pores, aggregates and micro-cracks in concrete can give rise to the differences in electrochemistry, and consequently generate micro galvanic corrosion cells on steel reinforcement. At a macro scale, spallings and delaminations in structures, repairs at damaged sites, and exposures of different parts of a large concrete element to different environments, can initiate macro galvanic corrosion cells and lead to serious corrosion damage in concrete structures.

CONSTRUCTION REQUIREMENTS

Reinforcing steel shall be protected from damage at all times. When placed in the work and before concrete is placed, reinforcing steel shall be free from dirt, oil, paint, grease, loose mill scale, thick rust, any dried mortar and other foreign substances. A thin layer of powdery rust may remain. All reinforcing steel required for superstructure concrete, such as slabs, girders and beams and top slabs of culverts with more than a 4-foot span, shall be held securely in correct position with approved metal or plastic bar supports and ties. Reinforcing bars shall be positively secured against displacement. For bridge decks and top slabs of culverts, bars in the top mat shall be tied at all intersections except where spacing is less than or equal to 12 inches in each direction, in which case

alternate intersections shall be tied. At other locations, the bars shall be firmly tied at alternate crossings or closer. The steel shall be tied in the correct position with proper clearance maintained between the forms and the reinforcement. The contractor shall construct the unit as shown on the plans. Measurements to reinforcing steel will be made to the centerline of bar, except where the clear distance from face of concrete is shown on the plans.

Bars shall not be spliced, except as shown on the plans or as directed by the engineer. Mechanical bar splice systems, as shown on the plans, shall be capable of developing 125 percent of the specified yield strength of the bar being spliced and shall be installed in accordance with the manufacturer's recommendations and as modified herein.

The contractor shall furnish to the engineer a manufacturer's certification stating that the mechanical bar splice systems are in accordance with this specification. The certification shall include or have attached specific results of tests showing yield and ultimate tensile load capacities. The splicing system may attach directly to the bars being coupled or may be of a type that provides reinforcing bars of like size that lap with the bars being joined. A threaded type splice system will be required where clearance considerations require the splicing device to be placed flush to the face of the construction joint for the initial concrete placement.

Reinforcing bar lengths shown in the bill of reinforcing steel may require modification to accommodate the specific mechanical bar splice system that will be used. The contractor shall determine the actual reinforcing bar lengths to accommodate the manufacturer's recommendations for installation of the mechanical bar splices.

COMPOSITE COLUMNS AND FRAMES

When the stanchions in steel frames were first encased in concrete to protect them from fire, they were still designed for the applied load as if uncased. It was then realized that encasement reduced the effective slenderness of the column, and so increased its buckling load. Empirical methods for calculating the reduced slenderness still survive in some design codes for structural steelwork.

This simple approach is not rational, for the concrete encasement also carries its share of both the axial load and the bending moments. More economical design methods, validated by tests, are now available.

Where fire protection for the steel is not required, a composite column can be constructed without the use of formwork by filling a steel tube with concrete. A

notable early use of filled tubes (1966) was in a four-level motorway interchange. ⁽⁴⁾ Design methods are now available for their use in buildings.

In framed structures, there may be composite beams, composite columns, or both. Design methods have to take account of the interaction between beams and columns, so that many types of beam-to-column connection must be considered. Their behaviour can range from 'nominally pinned' to 'rigid', and influences bending moments throughout the frame. Two buildings with rigid-jointed composite frames were built in Great Britain in the early 1960s, in Cambridge and London. Current practice is mainly to use nominally pinned connections. In buildings, it is expensive to make connections so stiff that they can be modeled as 'rigid'. Even the simplest connections have sufficient stiffness to reduce deflections of beams to an extent that is useful, so there is much current interest in testing connections and developing design methods for frames with 'semi-rigid' connections.

MATERIALS PROPERTIES

Information on the properties of structural steel, concrete, and reinforcement is readily available. Only that which has particular relevance to composite structures will be given here. For the determination of the bending moments and shear forces in a beam or framed structure (known as 'global analysis') all three materials can be assumed to behave in a linear – elastic manner, though an effective modulus has to be used for the concrete, to allow for its creep under sustained compressive stress. The effects of cracking of concrete in tension, and of shrinkage, can be allowed for, but are rarely significant in buildings.

Rigid-plastic global analysis can sometimes be used, despite the profound difference between a typical stress-strain curve for concrete in compression, and those for structural steel or reinforcement, in tension or compression. Concrete reaches its maximum compressive stress at a strain of between 0.002 and 0.003, and at higher strains it crushes, losing almost all its compressive strength. It is very brittle in tension, having a strain capacity of only about 0.0001 (i.e. 0.1mm per metre) before it cracks. The Steel yields at a strain similar to that given for crushing of concrete, but on further straining the stress in steel continues to increase slowly, until the total strain is at least 40 times the yield strain. The subsequent necking and fracture is of significance for composite members only above internal supports of continuous beams, for the useful resistance of a cross-section is reached when all of the steel yields, when steel in compression buckles, or when concrete crushes.

Resistances of cross-sections are determined ('local analysis') using plastic analysis wherever possible, because results of elastic analyses are unreliable, unless careful account is taken of cracking, shrinkage, and creep of concrete, and also because plastic

analysis is simpler and leads to more economical design.

STANDARDS AND RECOMMENDATIONS

As the author is most familiar with the situation in Europe the treatment in this paper will focus on the design methods as covered by European standards and in particular by the Eurocodes. The column base connection is a typical detail where steel and concrete meet. But in addition to steel and concrete there is in effect a third element and that is the connecting element in the form of anchors or fasteners. Each of these three composing elements is covered by Eurocodes. But unfortunately the development of these Eurocodes was not fully coordinated so that inconsistencies still exist in the various design approaches as will be illustrated in this paper. The situation is as follows:

Steel - In EN1993-Eurocode 3 all the design rules for joints have been collected in a separate part of Eurocode 3: EN1993-1-8. In this part the design of column bases is not treated separately but is integrated in the so-called "component-approach". The advantage is that the rules are fully consistent with the design approach for steel-steel connections. However, this way of presentation makes the rules not easy accessible for users. The rules are based on the results of a project earned out within the framework of the European Project COST C I (Semi-rigid behavior of civil engineering structural connections) and the Technical Committee 10 of ECCS (European convention for constructional steelwork). For background information refer to a recent special issue of Heron.

Concrete - For concrete aspects reference is made to EN1992-1-1 but this code does not give specific rules in all cases as will be demonstrated later. Furthermore the rules are only applicable if the anchorage has sufficient deformation capacity. This is often not the case for short anchors.

RESEARCH METHODOLOGY

The methodology of this research consists of five sequential stages as follows:

a) *Literature review.* Establish the concepts of composite steel-concrete structural element and its current design applications specified in the cited Eurocode norms. Then, the relevant equations, parameters and methods of calculation for the composite steel-concrete systems are established. This study is focusing on the beams, to demonstrate the approach of the proposed system.

b) *Cost parameters.* Define the parameters in the composite steel-concrete design process that affect the cost of materials. This would include the dimensions of the different steel elements, and the

different steel and concrete grades available in the market.

c) *Design phase.* The design phase utilizes the automatic calculations and programming powers of the spreadsheet environment with its macro capabilities. The design phase consists of four stages as follows:

1. Structural design computer program. Implementation of design variables and design procedures and equations as per the Eurocodes. It automates the design process for accuracy and speed purposes.

2. Cost estimating computer program. The proposed program uses optimization solving methods like Newton-Raphson method, direct tangent methods, or descendant steps in order to estimate total cost of materials included Excell Microsoft spreadsheet programs.

d) *Validation and implementation.* The functionality of the cost optimization support system is then tested in an iterative mode to ensure reliability prior to final implementation. Upon successful testing, parametric cost studies are conducted to determine the relationship between the structural element dimensions and their costs.

CONCLUSION

In this paper a simplified method for the design of composite columns in fire situation was presented, consisting in taking into account the temperature variation in the column along the length as well as in the cross section. In order to implement the analysis, a model of a column under fire was described based on the heat transfer laws, as well as a three-dimensional finite element formulation and its implementation in a computer code. The program allows the analysis of either homogeneous or composite columns under fire.

The method was then used for the analysis of a composite column consisting of a steel tube filled with reinforced concrete submitted to axial load under fire. For the example, the results were compared to the design load obtained for the procedure given in based on tabular data, EN 1994-1-2: 2005, resulting in considerable differences. These differences suggest that a more detailed analysis can, in this case, lead to lighter and cheaper structures. The results were also compared to the ones presented by Twilt et al. (1994), with good agreement. In the presented example, the moisture content of concrete was shown to be an important parameter, causing a 22% variation in the design load compressive resistance for a 120 minutes fire.

The paper proposes the cost optimization of the composite I beam floor system. This system consists

of a reinforced concrete slab of constant depth and non-symmetrical welded steel I beams. The optimization was performed by the nonlinear programming approach (NLP). An NLP optimization model for composite I beam floor system was thus developed. The objective function of the structure's manufacturing costs was subjected to a rigorous system of design, load, resistance and deflections inequality constraints, defined in accordance with Eurocode 4 to satisfy both the ultimate and the serviceability limit states.

To accomplish the above conditions, the model incorporates: (i) a design module that performs the design of composite beams; (ii) a cost module that computes the total cost of composite beams; and (iii) an optimization module that searches for and identifies optimal/near – optimal design alternatives.

Corrosion of steel in concrete continues to be a major issue for asset managers in the world. Hundreds of papers are being published in this area every year regarding corrosion behaviour, influences of factors, techniques for monitoring, laboratory simulation and acceleration, and service life prediction. A great deal of progress has been made on the above aspects through decades of efforts and contributions made by corrosion engineers and material scientists. The corrosion mechanisms of steel and related processes in concrete have been investigated to a wide and deep extent. However, there is still a lack of detailed information and convincing evidence on how chloride ions attack the passive film on the reinforcement steel in concrete; what relationship exists between free chloride and bonded chloride; how corrosion products affect the corrosion processes including the electrochemical reactions, transport of oxygen, chloride, hydroxyl and ferrous ions; and the possibility and mechanism of stress corrosion cracking or hydrogen induced embrittlement in prestressed concrete elements, etc.

The factors that can cause or affect corrosion of steel in concrete have been intensively studied, and the understanding of the effects of some factors on corrosion of steel has been employed to improve the durability of structures. For instance, some additives incorporated to reduce the porosity of concrete; the cover concrete and the strength of concrete have been increased and the w/c ratio decreased for the protection of reinforced concrete elements in corrosive environments. However, there are still not many direct and sound pieces of evidence supporting the explanation of the effects of those factors. For example, the complete mechanisms of some mineral and chemical additives influencing corrosion of reinforcement are not very clear. Even though extensive studies on the influences of concrete properties and environmental factors on corrosion of reinforcement have been carried out, the

understanding of the interaction among these factors is still superficial and limited. Particularly, no sufficient research work has been done on the interaction and synthetic effects of different factors, such as environmental temperature, wetness of concrete, permeability of the cover concrete, and the tolerance of the amount of reinforcement corroded before cracking in cover concrete takes place. The investigation on this aspect is of more significance from a practical point of view, because in the field, it can not be expected that there is only one factor operating.

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