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REMARQUES • BEMERKUNGEN • COMMENTS

A Survey of Using Steel in Combination with Other Materials

Relevé sur l'utilisation d'acier en combinaison avec d'autres matériaux

Übersicht über die Verwendung von Stahl in Kombination mit anderen Materialien

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In the introductory report (164), we expressed the hope that the prepared and free discussions contributed toward Theme IIa at the Ninth Congress IABSE would combine with the introductory report to form an authoritative world-wide survey of the theme subtopics as of 1972. Indeed, after the introductory report was published in 1970, we received a number of private communications referring to important earlier studies and applications not included in the report. Many of these omissions have either been discussed, or referred to, by the authors of the prepared discussions presented at the Ninth Congress. Other contributions, including more recent material published elsewhere, will be discussed in this final report.

The response to the request for prepared discussions on the INTERACTION OF DIFFERENT MATERIALS and the numerous new articles which have been published on this subject since 1970 make it evident that the art of combining steel with other materials is being actively explored and extensively utilized throughout the world. However, it is clear that combining steel with concrete to form composite beams, columns and floor systems has been receiving the greatest attention. Composite steel-concrete construction represents one of the older and more significant exploitations of the interaction of different materials. Other forms of construction that utilize interaction and are treated in this final report include sandwich construction, hybrid steel construction, prestressed steel structures and cable-stayed steel bridges.

COMPOSITE STEEL-CONCRETE CONSTRUCTION

The papers presented at the Ninth Congress by Messrs. Daniels (165), Hope-Gill (166), Maeda (167), Roderick (168), and Naka (169) made it clear that problems of continuity in composite structures are of major concern in current research. The remaining contributions dealing with the topic of composite construction (170) (171) (172) (173) (174) were addressed to problems encountered in simple elements.

Composite Steel-Concrete Beams

Continuity - The use of composite beams in bridges and multistory buildings brought forth a number of questions that became the subject of systematic research only during the last decade. The early static tests of continuous beams (54) (55) (56) (57) were followed by investigations of beam-to-column connections (166) (168) and by detailed investigations of the negative moment region of continuous beams (168) (175) (176) (177). Tests have shown that properly reinforced continuous composite beams can develop negative moments equal to the ultimate bending strength of their positive moment region. Furthermore, plastic hinges with adequate moment-rotation capacity can be developed under combined negative moment and shear. These studies furnished the basic tools for investigations of composite beams as part of building frames.

Continuity in frames requires reliable connections. This subject earlier had not received as much attention as it deserves. Dobruszkes, Janss and Massonnet (178) reported on tests of connections between composite beams and concrete columns, and between fully encased steel beams and columns. Roderick (168) briefly discussed tests on exterior and interior connections of composite beams to fully encased columns carried out by Ansourian at the University of Sydney. Naka, Wakabayashi and Murata (169) listed several references to tests of beam-to-column connections encased in reinforced concrete. All found that concrete encasement substantially increases the strength of a connection. An interesting type of a semi-rigid connection of a composite beam to a steel column was developed by Johnson and Hope-Gill (166). It offers many of the advantages of a rigid connection, but lower in-place cost. The connection can develop appreciable strain hardening before the maximum load of the continuous beam is attained.

Concurrent fatigue tests of continuous beams were aimed at bridge applications. Maeda and Kajikawa (167) investigated the fatigue strength of a tension flange with stud shear connectors. The tests, including both direct tension specimens and beams subjected to negative bending, indicated a substantial reduction of the tension flange fatigue strength in the presence of shear connectors. This reduction tended to be smaller in bending tests than in direct tension tests. These results were in good agreement with earlier tests (39) (179) (180). Roderick (168) tested a continuous composite beam in fatigue and concluded that the fatigue life of stud connectors compared favorably with the values given by the British Standard Code of Practice CP117: Part 2 (36). Fatigue strength of shear connectors in continuous composite beams had been investigated in an earlier study at Imperial College (35) and in extensive investigations at Lehigh University (37) (165).

To avoid the deleterious effect of connectors on the fatigue strength of tension flanges, it is a common United States practice to omit shear connectors from a portion of, or throughout, the negative moment region of a continuous beam. The Lehigh investigations have shown that in such cases additional shear connectors must be provided near the points of contraflexure. The results of those studies have been incorporated in the AASHO Specifications (118) (181). Further studies of the negative moment region carried out at Lehigh University (165) have shown that the longitudinal reinforcement in the slab over the negative moment region should be at least 1% of the cross-sectional area of the slab; that most of this reinforcement should be placed near the top surface of the slab; and that it is reasonable to assume that the effective width of the concrete slab is the same throughout the beam length. Similar conclusions have been reported by Tachibana (182).

Lightweight Concrete - The results of systematic tests of composite beams with lightweight concrete slabs at Lehigh University and at the University of Missouri, referred to in the introductory paper (164), were published in 1971 (25) (26) and incorporated in the AISC Specification (183). In addition to determining the strength of shear connectors, these studies have shown that the strength of a composite beam with a slab of lightweight concrete is the same as for a beam with a slab of ordinary concrete of the same compressive strength. On the other hand, deflections are larger in beams with lightweight concrete. Accordingly, the design requirements based on beam strength should depend only on the strength of concrete while the deflection requirements should be also a function of concrete density.

Static and fatigue tests of stud connectors embedded in lightweight concrete were made in Great Britain by Menzies (184), who recommended design values for concrete with densities from 87 to 143 lb/cu. ft. Further research on lightweight concrete composite beams was reported by Roderick (168), Janss (170) and Ypeij (185). These studies generally substantiated the results of the above-mentioned American investigations.

Creep and Shrinkage - Long-term static tests of composite beams with lightweight aggregates were conducted at the University of Missouri (26) and at the University of Liege (170). Both studies demonstrated substantial deflection increases from creep and shrinkage. The Missouri investigators recommended that, in design, time-dependent deflection be taken as equal to instantaneous deflection.

Other studies of creep effects have been made recently in Germany by Hasse (186) and by Mainz and Wolff (187). In Great Britain, Menzies (188) analyzed data from the Moat Street Flyover taken during construction and for about two years thereafter. He found that after construction, effects of temperature changes obscured the small effects caused by shrinkage and creep. In the United States, Roll (189) analyzed the stresses and deflections due to differential shrinkage and creep in both shored and unshored beams in a New York State office building. He obtained excellent correlation between measured and theoretical deflections.

Precast Slabs - Composite beams with precast slabs connected to the steel members with high-strength bolts can be advantageous, particularly when on-site construction must be kept to a minimum or when traffic must be maintained during construction. In addition to Sattler (43), this type of construction was pioneered by Faltus (190) who used it for elevated railway bridges built in Czechoslovakia in the early sixties.

Marshall, Nelson and Banerjee (191) have continued Sattler's work on the use of high-strength bolts by making a series of push-out and beam tests at the University of Glasgow. They concluded that the load at first slip can be estimated using a friction coefficient of 0.45 for precast slabs on steel. A higher coefficient can be used for cast-in-place slabs. Beck and Heunisch (192) also made push-out and beam tests and concluded that design should be based either on an allowable coefficient of friction or on forces redistributed by slip. Research at Purdue University (45) (193) demonstrated that it is feasible to replace deteriorated highway bridge decks with precast, prestressed concrete slabs.

Beck and Heunisch (192) used bolted precast slabs in the construction of a 7-story building at Johann Wolfgang Goethe University in Frankfurt-on-Main. Other structures utilizing this type of composite construction included a few demountable overpasses and parking garages. Holloway (194) (195) described the Rosslare Harbor Viaduct and the Tivoli Bridge in Ireland as examples of structures reconstructed economically with precast composite units.

Miscellaneous - Among numerous additional studies, the load factor design for highway bridges developed on both sides of the Atlantic (196) (181) (197) (198) includes provisions for design of composite beams. Reddy and Hendry (199) made a thorough review of the results of British studies of simply-supported composite beams and derived equations for the ultimate bending strength of such beams. Repeated load tests of simple composite beams by Roderick (168) demonstrated that properly designed composite beams will not fail catastrophically, but rather by gradual deterioration. R. P. Johnson proposed design methods for consideration of longitudinal shear (200), transverse slab reinforcement (201) and deep haunches (202) in composite beams; the last proposal was based on experiments conducted at the University of Manchester (203). New studies of torsional properties of composite beams were reported by Heins and Kuo (204) (205). Janss joined the researchers interested in the use of checker plate (170) and L'Hermite joined those interested in the use of epoxy resins (173) for shear connection. Naraharirao (206) and Cran (207) reported on further studies of composite open-web steel joists.

Concrete Encased Steel Beams

Interest in concrete encased steel beams appears to be limited. Only one reference (169) to such beams was made in the contributions to the Ninth Congress, and only four other new references were found (194) (195) (208) (209).

According to Naka, Wakabayashi and Murata (169), steel frames encased in reinforced concrete are used extensively in Japan because of their excellent seismic resistance. Encased steel beams are an integral part of such frames. Their design is governed by the specifications of the Architectural Institute of Japan (210) and is based on extensive studies listed in the bibliography of Reference 169. The allowable bending moment for an encased steel beam is specified as the sum of the allowable bending moments of the steel beam and the reinforced concrete beam. Holloway reported on the use of precast concrete-encased steel beams in a footbridge at Balbriggan (195) and as parapet units for the Tivoli Bridge (194). The remaining two references were concerned with tests of concrete encased steel sections. Matty and Narasimhan (208) tested 24 simply-supported and 5 continuous beams to determine their moment-curvature relationships. Babb (209) reported on full-scale and model tests on two new, patented types of concrete encased steel sections.

Steel-Concrete Columns

The discussion of concrete encased steel columns in the introductory report (164) was concluded with the following statement: "It would seem...that the data and the tools necessary for the development of improved design methods for concrete encased steel columns are available and that improvements of code provisions are in order." The 1971 edition of the ACI Building Code (211) is available and a new British Standard CP117: Part 3 (212) is in draft form. Both include new design methods for steel-concrete columns.

Based on experimental and theoretical research by Furlong (107) (108) and by Knowles and Park (213) (214), the 1971 edition of the ACI Building Code redefined all types of composite columns as composite compression members reinforced longitudinally by either structural steel shapes, pipe or tubing with or without longitudinal reinforcing bars. Composite compression members now can be designed as beam-columns; prior to the 1971 Code rules were available only for the design of concentrically loaded columns. Subject to limitations on maximum stiffness and maximum radius of gyration of the composite cross-section, and to a few detailing rules, the strength of composite compression members is computed using the ordinary procedures for reinforced concrete members.

Following the decision in 1963 to use concrete-filled tubular columns in the multilevel interchange between the M4 and M5 Motorways at Almondsbury (215), exploratory tests were conducted at the Building Research Station and Imperial College. As has been reported in the introductory report, further investigations followed at Imperial College. These included analytical work that was checked against tests of concrete-filled circular tubes conducted at Imperial College (216), in Japan (217) and at Liege (218). A second series of tests at Liege (219) permitted a check of the analytical work for eccentrically loaded square and rectangular concrete-filled tubes. A computer program based on uniaxial strength of concrete was found to predict accurately the strength of the latter columns and the strength of slender circular columns with length-to-diameter ratios over 15 (220). More recent studies at Imperial College have been concerned with triaxial stress effects that augment the strength of short circular concrete-filled tubes (221). Another such attempt was reported by Janss (170).

The practical utilization of the research at Imperial College took three paths. The uniaxial computer program was used both to generate ultimate load tables for concrete-filled tubes (222) and to develop an empirical method for calculating the ultimate strength of concrete-filled square and rectangular columns (223). Finally, a draft was prepared of a design specification for composite columns in buildings and bridges (212).

In Japan, steel columns encased in reinforced concrete are used in frames (169). The allowable axial load and bending moment are computed either (1) as the allowable axial load on the concrete section and the sum of the allowable moments on the steel and concrete sections or (2) as the allowable moment on the steel section and the sum of the allowable axial loads on the steel and concrete sections.

Roderick (168) reported the results of tests of concrete encased steel columns bent about both principal axes. In nearly all tests the theoretical column instability was reached shortly after the steel had begun to yield. The theoretical collapse loads were lower than the actual collapse loads for eccentricities of up to 0.8 in. about any centroidal axis. Good agreement with the theoretical solution was found also in tests of concrete-filled square steel tubes eccentrically loaded about their diagonal axis.

The development of two additional computer programs for concrete-filled tubular beam-columns was reported recently from Canada (224) and the United States (225). Another paper discussed prestressing of tubular columns through the use of expansive cement (226).

Two earlier studies of concentrically loaded concrete-filled tubes (227) (228) were discussed in the introductory report, but the corresponding references were omitted from the bibliography.

Steel-Concrete Slabs

The developmental work leading to the use of composite steel-concrete plates as blast resistant hatch covers, mentioned in the introductory report, is described in Reference 229. Composite steel-concrete plates are also well suited for mine shaft and tunnel liners (230) (231). While ordinarily the concrete and steel connection is mechanical, L'Hermite (173) proposed to bond the two with epoxy resin applied to blast-cleaned steel plates just before placing the concrete. In these applications, the steel plate serves both as a tension or shear carrying member and a concrete form.

A brief, interesting history of the development and current status of cellular steel floors was presented by Dallaire (232). The interaction of composite sheet steel flooring with concrete has been under investigation at the University of Iowa (134) (233). The behavior of these systems was described by Schuster (172) for simple one-way slabs and by Porter and Ekberg (171) for simply supported two-way slabs.

Composite Steel-Concrete Structures

Since the individual elements, i.e. beams, columns, slabs and walls of a structure may be composite or noncomposite and, furthermore, of several different types, the choice of possible structural systems is substantial.

In bridge construction, the most common structural system is a steel beam and girder framing acting compositely with a concrete slab.

In building construction, the older fully encased steel framing and the newer unencased steel framing acting compositely with the floors are probably the two best known systems. As we have seen earlier, a modification of the fully encased framing is used extensively in Japan (169) because of its excellent seismic resistance. Unencased steel framing acting compositely with the floors is used extensively in the United States. Roderick's studies of connections (168) suggest the use of fully encased columns in combination with ordinary unencased composite beams. A similar system was developed recently by F. R. Khan for medium-rise tall buildings (234). In this system, the gravity loads are supported by steel columns, both exterior and interior, while the wind loads are resisted by exterior concrete walls reinforced with the exterior steel columns and acting as a vertical box cantilever. The exterior columns are encased in concrete walls. In the three buildings discussed in Reference 234, the floors were of ordinary steel-concrete composite construction. The buildings, located in Houston, Chicago and New Orleans, are 24, 36 and 50 stories high.

SANDWICH CONSTRUCTION

None of the contributions to Theme IIa dealt with sandwich panels and only one (235) among the numerous other contributions to the Ninth Congress dealt with sandwich construction. It would seem then that there is little interest in the use of sandwich plates as structural construction elements. However, some recent references suggest that the interest is not entirely absent, either in Europe (235) or in the United States (236).

Several recent articles by Jungbluth (235) (237) (238) described the properties, manufacture and applications of steel-polyurethane sandwich panels that consist of two steel sheet face plates and a comparatively thick core of foamed polyurethane. The principal use of the panels is for walls but they have been used or proposed for use as a self-supporting roof and for cable-supported roofs. Reichard (236) discussed paper honeycomb-core panels used by the building industry for walls of single-story residences. The panels are faced with steel, aluminum, fiber-reinforced plastics or other materials. The article concluded with the statement that the construction industry in the U.S. is now using several different sandwich panel systems and is contemplating the use of others.

HYBRID STEEL CONSTRUCTION

Two contributions to the discussion were concerned with hybrid sections. In one, Bo and Daddi (174) pointed out that unsymmetrical hybrid sections with bottom flanges made of 100 ksi yield steel would improve Preflex beams. The other paper presented an analysis and four tests of hybrid columns (239) with 100 or 50 ksi steel flanges and 50 or 36 ksi steel webs.

The results of the hybrid girder fatigue tests at the University of Texas, referred to in the introductory report, have been published (240) (241) (242). The reports contain information on fatigue tests of 71 plate girders having stiffened webs 3 or 4 feet deep of 36 ksi steel and flanges of 100 or 50 ksi steels.

The use of hybrid girders in the United States has grown rapidly since the 1969 adoption of specifications for their design (84) (118). Today, hybrid girders with 50 ksi flanges and 36 ksi webs are used extensively for highway bridges. The discussion provided no information on the use, if any, of hybrid girders in other countries. On the other hand, hybrid construction, i.e. the use of different steels in various parts of the same structure, has been common for decades. Structures of this type can be found throughout the world. The recent development of new steels has increased the importance of hybrid construction and widened its use.

PRESTRESSED STEEL STRUCTURES

For this discussion, it seems useful to distinguish between prestressing of individual components (e.g. a girder) and prestressing of the whole structure (e.g. a cable-supported roof).

Two contributions were directed to the first subject. Bo and Daddi (174) proposed to build Preflex beams using hybrid girders with bottom flanges of 100 ksi steel. In the second contribution, Tochacek, Rosenkranz and Ferjencik (243) outlined an extensive research and development of prestressed steel that has been in progress since 1960 in Czechoslovakia. One recent news item (244) dealing with prestressed elements is pertinent here. It reports the first -- and thus far the only -- use of Preflex beams in the United States; this type of construction was selected primarily to reduce construction depth.

The scarcity of Western literature on this subject suggests that prestressed steel components have been used there only infrequently, probably because they do not offer an economic advantage. On the other hand, the literature cited in the introductory report and the contribution by Tochacek, Rosenkranz and Ferjencik suggest that prestressed steel components are used in Eastern Europe.

One contribution to Theme IIa dealt with prestressing of steel structures (245). Describing examples of prestressed steel structures built in Czechoslovakia, it included, among others, cable-supported roofs, strengthening of existing bridges by prestressing, cable-supported pipe crossings and guyed towers. Further information on this general subject may be found in Reference 246. It should be mentioned that Theme IIIa of the Ninth Congress was devoted specifically to the subject of cable-supported roofs and the contributions to that subject covered more than 100 pages of the Preliminary Report (247). Five other contributions to various themes in the same Report dealt with cable-stayed bridges. Recent papers covering these and other types of prestressed steel structures are too numerous to be included in this final report.

Prestressing of steel structures is a widely used art that includes many varied forms. It is noteworthy, however, that East European countries treat it as a separate, distinct discipline.

CABLE-STAYED STEEL BRIDGES

The subject of cable-stayed bridges was introduced in Theme IIa by reference to six earlier papers and in Theme IIIa by Professor Leonhardt's introductory paper (248). Outlining recent trends and further developments, Leonhardt pointed out several advantages of cable-stayed bridges as compared to suspension bridges. He concluded that cable-stayed bridges are particularly suitable for spans in excess of 1,000 meters and may even be used for spans of 1,500 meters in the future. Leonhardt suggested also that there is a trend toward a large number of cables in one plane; that the use of aerodynamically stable deck cross-sections is particularly desirable for long spans; that parallel wire cables increase stiffness and reduce weight; and that a newly developed process of socketing with plastics instead of zinc will increase the fatigue strength of cables and lead to higher working stresses. In his discussion (249), Thul expressed general agreement with Leonhardt's views. However, Thul expects suspension bridges to remain dominant in very long spans. Thul's discussion of cable properties, socketing and delayed cracking of wires was a particularly useful contribution. Other contributions to the Ninth Congress included discussions of: a cable-stayed bridge with a three-level deck (250); the construction of the bridge over the railroad station in Ludwigshafen (251); the investigation of the aerodynamic behavior of the Toyosato Ohhashi bridge in

Japan (252); and another method of socketing and protecting parallel wire cables (253). Additional information on cable properties can be found in Reference 254.

It is interesting that, with one exception, all contributions pertaining to cable-stayed bridges were authored by German engineers. On the other hand, a review of the recently published reports indicates that cable-stayed bridges are receiving considerable attention throughout the world. General surveys have been published in India (255), the United States (256) and elsewhere (257). Numerous articles have described new bridges in Great Britain (258), Canada (259), Australia (260), Czechoslovakia (261), the Soviet Union (262), the United States (263), France (133), Germany (264), Austria (265), Argentina (266) and elsewhere; and plans for new bridges (267) (268) (269) (270). Contributions to the theory of design are also multinational (271) (272) (273) (274) (275) (276) (277) (278) (279) (280) (281). It also should be pointed out that some of the articles on cable-stayed bridges deal with problem areas (249) and a catastrophic failure (282) (283) (284) (285). Report 282 made it clear, however, that this failure was unrelated to the cable-stayed feature of the bridge.

This brief review of the recent contributions to the field of cable-stayed steel bridges has highlighted one of the most significant structural developments of recent years: the spread of this construction throughout the world. Counting bridges that have been completed and those now under construction, there are presently more cable-stayed steel bridges outside than inside the German Federal Republic. This development alone is bound to lead to further innovations that will make the cable-stayed steel bridge an even more effective tool of the bridge builder.

CONCLUDING REMARKS

This survey would appear incomplete unless it included at least a thought or two on what the past suggests for the future.

In building construction we can expect more complete integration of the components into systems. In low-rise structures, walls and floors will be integrated into room modules before they are brought to the site. In high-rise structures, the development of submodules can be predicted from recent experience. Frames will probably be integrated with curtain walls to serve both as a structure and a temperature and sound barrier. This subsystem may also include electrical and mechanical services. Floors, ceilings, wiring and ducts are candidates for another subsystem.

In bridge construction we can expect to see extensive use of single-span preassembled bridges for short spans. In medium spans, one or two girders with an appropriate portion of the slab are likely to be subassembled before lifting the unit into place. Transverse and longitudinal continuity can be provided through prestressing or some other means. In the long span range, we have already seen full-width modules lifted in place, joined longitudinally and supported by cable stays or suspended from cables.

The development of improved materials and better design tools will lead not only to more economy, but also to more useful structures. As in the past, the structures of the future will play an important part in improving the quality of life.

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For brevity, the following abbreviations have been used in this bibliography:

ACI	American Concrete Institute
AISC	American Institute of Steel Construction
AISI	American Iron and Steel Institute
AASHO	American Association of State Highway Officials
ASCE	American Society of Civil Engineers
IABSE	International Association for Bridge and Structural Engineering

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SUMMARY

This final report, combined with the introductory report on interaction of steel with other materials, constitutes a survey of the state-of-the-art in composite steel concrete construction, sandwich construction, hybrid steel construction, prestressed steel structures and cable-stayed bridges as of the middle of 1972.

RESUME

Ce rapport final forme, ensemble avec le rapport introductif sur l'interaction de l'acier avec d'autres matériaux, un aperçu sur l'état actuel de la construction en acier-béton, de la construction sandwich, la construction hybride, les structures en acier précontraint ainsi que des ponts à haubans, vers le milieu de l'année 1972.

ZUSAMMENFASSUNG

Dieser Schlussbericht bildet zusammen mit dem Einführungsbericht über die Wechselwirkung von Stahl mit anderen Materialien eine Uebersicht über den Stand des Stahlbetonbaues, der Sandwichkonstruktion, des hybriden und vorgespannten Stahlbaues sowie der Schrägkabel-Brücken um die Mitte des Jahres 1972.

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