New insights and future trends in composite construction – results of current research

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Kurzfassung

Der Verbundbau ist als Vereinigung des klassischen Stahlbetonbaus und dem konstruktiven Stahl- oder auch Holzbau seit vielen Jahren sehr erfolgreich in der Baubranche vertreten und deshalb Schwerpunkt zahlreicher Untersuchungen. Nicht nur konstruktiv, sondern auch normativ befindet sich die Bauweise in einer immerwährenden Weiterentwicklung. Gerade vor dem Hintergrund der anstehenden nächsten Generation des Eurocodes 4 werden neue Erkenntnisse gewonnen und ergänzt, um die Bauweise besser zu verstehen und eine wirtschaftlichere Bemessung zu ermöglichen. Besonders im Vordergrund steht hierbei auch die Kompatibilität zum Eurocode 2.

In diesem Beitrag soll ein kurzer Überblick in die aktuellen Untersuchungen im Bereich des Verbundbaus am Institut für Massivbau der RWTH Aachen University (IMB) gegeben werden und deren Relevanz für verschiedene Einsatzgebiete sowie die zukünftige Normung aufgezeigt werden. Nach einem kurzen Überblick über die aktuelle Normung auf europäischer Ebene wird die geplante Weiterentwicklung in Form der nächsten Generation des Eurocode 4 dargestellt. So sollen zum Beispiel Bemessungsgrundsätze für Verbundträger mit Stegöffnungen aufgenommen werden und die Bemessung von ausbetonierten Hohlprofilverbundstützen im Brandfall in einem neuen Anhang des Eurocode 4 geregelt werden. Zudem wird für Verbunddübelleisten, die umfassend am IMB erforscht werden, eine CEN Technical Specification erarbeitet. In diesem Zusammenhang werden in diesem Beitrag Auszüge aus aktuellen Forschungsprojekten vorgestellt. Neben neuartigen Konstruktionsweisen steht insbesondere auch der Einsatz von hochfesten Materialien im Vordergrund aktueller Entwicklungen. Für den konstruktiven Hochbau werden daher materialsparende Hochleistungsverbundstützen mit hochfesten Stählen in verschiedenen Ausführungsvarianten und Bemessungsfällen erforscht. Verbundträger oder Verbunddecken mit großen Öffnungen sind aufgrund der steigenden Installierungsgrade ebenfalls für den konstruktiven Hochbau relevant. Dabei sind vor allem die Traganteile des Betons im Bereich der Öffnungen von großer Bedeutung, da diese aktuell bemessungstechnisch nicht eindeutig berücksichtigt werden.

Keywords: Verbundbau, Verbundstützen, Verbundträger, Kopfbolzendübel, Verbundträger mit Stegöffnungen

Abstract

Composite construction, as a combination of traditional reinforced concrete and structural steel as well as timber, has been very successful in the construction industry for many years. Therefore, it has been the focus of numerous investigations. Not only in terms of design but also in terms of standardization, this construction method is in continuous development. Especially considering the upcoming next generation of Eurocode 4, new insights are being gained and added to better understand the construction method and enable more economical design. Compatibility with Eurocode 2 is a key consideration.

This paper presents an overview of current research in the field of composite construction at the Institute of Structural Concrete at RWTH Aachen University (IMB) and demonstrate its relevance for various applications and future standardization. After a brief overview of the current Eurocodes, the current development of the next generation of Eurocodes is presented. For example, design approaches for composite beams with web openings are being developed, and the structural fire design of concrete-filled hollow section composite columns will be regulated in a new Annex of EC4. Furthermore, a CEN Technical Specification is being developed for composite dowel bars that are extensively researched at the IMB. In this context, ongoing research projects and corresponding new developments are presented.

DOI: 10.18154/RWTH-2023-06672

In addition to innovative constructions, the use of high-strength materials is particularly essential in current developments. For structural engineering, material-efficient high-performance composite columns with high-strength steels are being investigated in various design variants and cases. Similarly, in structural engineering, composite beams or composite slabs with large web openings are becoming relevant due to increasing installation requirements. In this case, the load-bearing capacity of the concrete around openings is particularly important as it is not explicitly considered in current design rules.

Keywords: Composite construction, composite columns, composite beams, headed studs, composite beams with web openings

1 Introduction

1.1 Composite construction

Composite construction is an effective building design that complements the common approaches of pure steel and structural concrete, allowing for optimal utilization of both materials and their load-bearing capacities. Initially, this construction method (the middle of the 19th century), concrete and steel were already combined but with often more the increase of fire resistance and less the favourable impact on the load-bearing capacity in mind. Due to this fact, the steel was embedded into the concrete with no shear connectors so that brittle shear failure often occurred. At the beginning of the 20th century, the cross sections were separated but the importance of their connection was only partly recognized, still relying mostly on adhesive bond. The constructive connection of steel and concrete then moved into focus for researchers and engineers in Switzerland, Sweden, and Austria in the 1930s. It has been suggested that at the same time composite structures were also built in Germany, but these were not well documented [1]. The technological progress only found its way to Germany at a later stage, so that composite structures became relevant in the construction industry in the late 1940s [1; 2]. But it took another 20 years till the first standards for composite constructions were established in Germany [1].

The capabilities of excellent material properties (great tensile strength of the steel and the compressive strength of the concrete) complement each other well. In comparison to regular structural concrete which also utilises the tensile strength of the reinforcement, the steel profiles possess a bending stiffness due to their shape which can be considered for e.g., the shear force resistance. Due to this fact, composite structures often have an advantage in terms of smaller dimensions and weight (less resource consumption) due to their higher strength and utilisation of cross sections. For both cross sections participating in the load transfer, especially bending forces, a shear-resistant connection has to be implemented. The connection of the two partial cross sections still has been the focus of investigation for many years. In composite beams or columns, headed studs (Fig. 1e) and composite dowels have established themselves as the leading shear connector. Whereas headed studs are part of the current Eurocode 4 (EC 4) [3], composite dowels are only regulated in Germany in a design approval [4]. In the last years, multiple investigations have taken place to assess the bearing behaviour of various dowel forms, i.e. composite dowels [5–7]. The composite dowels have shown themselves to be superior to headed studs in multiple aspects because the lack of welding points, which makes them easier to construct an less prone to fatigue [8–13]. In the future, it is planned to regulate composite dowels on a European level to simplify their implementation.

Composite construction finds application in various areas in structural engineering. In multi-storey buildings, columns (Fig. 1a – d), girders/beams (Fig. 1e) or floors/ceilings can be established in form of composite structures. The smaller cross sections enable an increase of usable space making composite structures economically viable. Composite floor constructions allow a high degree of installation due to their resolved cross section. The installation of technical equipment in the floors requires openings in the steel web, so that lines can be directed perpendicular to the span direction. Integral floor systems offer a sustainable solution for multi-storey buildings thanks to their flexibility and reusability of space and the structure itself [14–18]. For composite structures, the choice of materials is not only limited to steel and concrete. For example, the use of wood instead of steel which expand the field for timber applications for a more sustainable development [19; 20].

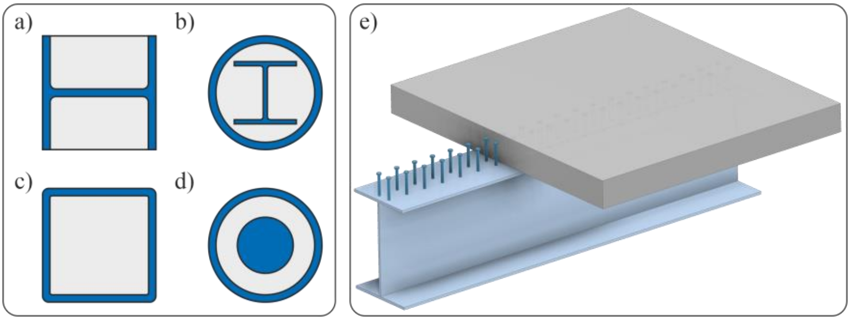

Fig. 1 Different types of composite columns (a – d), construction principle of composite beams with headed studs (e)

Another field of application of composite structures are infrastructural buildings, in particular bridges [21]. Being flexible regarding the form finding of the cross section, the high degree of prefabricating and the shorter construction time, replacement buildings crossing roads or railroads of short to medium span widths are increasingly being constructed using composite constructions. The construction time can even be accelerated using (partly) prefabricated composite girders [22; 23]. Such approaches combine the benefits of composite structure with those of prefabricated parts resulting in reduced construction time and weight by dispensing with falsework and optimized use of materials.

1.2 European standards for composite construction

The Eurocodes represent European standards on the design and construction of construction of multi-storey and bridge constructions. In 2012 the Eurocodes have been implemented as binding standards in Germany [24]. The design and construction of composite structures for Germany are regulated in DIN EN 1994-1-1 in form of EC4 with National Annex [3; 25] which refers to the standards for steel construction and structural concrete, Eurocode 3 [26] and Eurocode 2 [27], respectively. The roadmap foresees an introduction of the new generation of Eurocode 4 in or around 2025 [24]. Nonetheless, several aspects of composite construction are still not considered in the current developments of the Eurocode 4, e.g., the use of high-strength materials in composite columns and the use of composite dowels. This is why research projects are being carried out and planned to gain knowledge that can be used in the following Eurocode and help optimizing composite constructions for future applications and frameworks.

2 Research projects

In the following, various research projects that deal with new developments in the field composite structures are presented. These projects are in part carried out at RWTH Aachen University, i.e., the Institute of Structural Concrete (IMB). The first project comprises high performance composite columns using high-strength steels and a simple construction principle without welding. The second project investigates composite beams with large web openings with the goal to elaborate a consistent design model. The third area of investigation deals with composite dowels and their behaviour under monotonic and cyclic loadings, or under various conditions, i.e., cracked concrete.

2.1 High performance composite columns

With increasing demands for design, versatility, and resource efficiency, the construction industry is constantly faced with challenges. In structural engineering, hollow section composite columns are commonly used, allowing for a high load resistance with relatively small component dimensions using composite profiles. Over 100 years ago, concrete-filled steel tubes were already employed to achieve increased load-bearing capacity compared to steel or reinforced concrete [28]. The good fire protection properties of the concrete column and the better rotational capability of the steel column could be combined in one structural element. There are various types of composite columns which differ in their structure:

- Steel profiles embedded in concrete (Fig. 1a),

- Steel profiles partly embedded in concrete, profiles with chambered concrete,
- Concrete filled hollow sections (Fig. 1c), optional with embedded core (Fig. 1b and d).

However, this construction method is now reaching its limits, as precast concrete columns in structural engineering are often superior from both technical and economic point of view. New concepts and materials are necessary to maintain the competitiveness of composite steel columns in the long term. The use of high-strength materials can help composite columns to bridge the technology gap to expand market share and address sustainability. The implementation of these materials has economic and ecologic advantages because of slender cross sections and thus less space used. Using concrete filled hollow sections with an embedded steel core, a good fire resistance can be achieved [29]. The possibility and resulting advantages of using high-strength materials in composite construction was already shown [13; 30].

The use of high-strength materials in composite columns is currently limited by the EC4 [3] to constructive steel S460. The design principles rely mostly on outdated investigations carried out in the last century and are accordingly limited to this state of the art. Even in the next generation of the EC4, the design of composite columns using high-strength materials cannot be included due to the lack of systematic and experimental investigations [29]. For this reason, several FOSTA (Forschungvereinigung Stahlbanwendung e.V.) research projects aggregated in the framework of the research cluster HOCHFEST ("high-strength") initiated to investigate the behaviour of high-strength materials, i.e., steel and concrete. Among other things, the load-bearing behaviour of high-performance composite columns is examined under room and fire temperature, or seismic loading [31–35]. This is intended to provide the necessary basis for future developments of the EC4 and the responsible technical committee CEN/TC 250/SC 4 for a technical specification of high-performance composite columns [29].

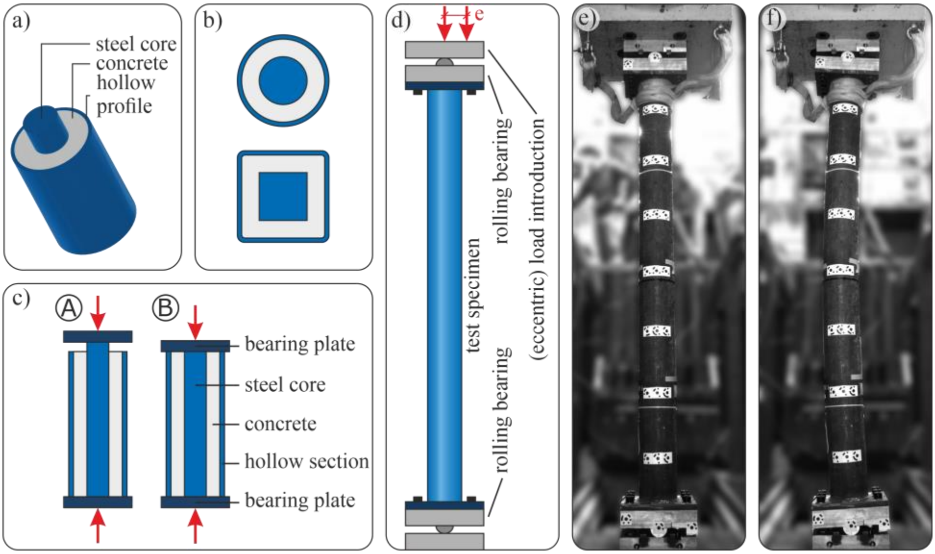

Fig. 2 a) Structure of high-performance composite column, b) investigated cross sections, c) stub-column test setup, d) test setup for stability tests, e) circular test specimen in initial state, f) circular test specimen in failed state (global buckling)

The FOSTA project P1501 „universal high-performance columns made of S960 without welding" [33] is a joint research project carried out by the RWTH Aachen University (Institute of Steel Construction and Institute of Structural Concrete) and the TU Braunschweig (Institute of Building Materials, Concrete Construction and Fire Safety). In this project, a new composite column concept using solid core and an encasing jacket made from high-strength steel (HSS) as well as ultra-high-strength steel (UHSS) filled with concrete is investigated under normal load and in case of fire. Regular composite structures using UHSS have high demands regarding welding works because of the material being prone to hot and cold cracking. The innovative composite column concept avoids the issue of high demanding welding work since the individual pieces are just placed inside each other and filled with concrete (Fig. 2a).

The load is introduced via the core which is responsible for carrying the normal force, whereas the purpose of the concrete and the encasing hollow section lies in increasing the flexural rigidity and the fire resistance, respectively. Within the framework of the ongoing research project funded by the AiF (Arbeitsgemeinschaft industrieller Forschungsvereinigungen "Otto von Guericke" e.V.), this composite column system using HSS and UHSS is being investigated in more detail by means of numerous experimental and theoretical investigations.

The experimental program comprises various small- and full-scale experiments. To analyse local phenomena separately, to assess the cross section properties and the load-bearing behaviour, small-scale tests were carried out: The focus lies on bond behaviour and load introduction [36], creep behaviour and load distribution, plastic normal load-bearing capacity (Fig. 2c) and temperature-dependent material properties. Based on the findings, full-scale specimens were dimensioned and tested in the form of stability investigations on pure steel cores and composite columns, investigations of the normal force-moment interaction of composite columns (Fig. 2d-f) and stability investigations of composite columns in case of fire [33].

2.2 Composite beams with web openings

In multi-storey and industrial construction, steel-concrete composite floor systems with a high degree of installation are increasingly used. Building services are routed through in the web openings of the beams to reduce the overall height (Fig. 3a). However, web openings of the beams create local disturbances, causing parts of the shear force from the web of the steel profile to be transferred into the concrete chord. This leads to additional, locally concentrated stresses in the remaining steel beam and the concrete chord, which need to be considered in the design of the floor beams and composite elements (Fig. 3b) [37]. Currently, the existing European design standard for steel-concrete composite construction, EC4 [3], does not address web openings in composite beams. Regulations for pure steel beams with web openings are covered in the DASt Guideline 015 [38]. However, it does not account for the shear capacity of the concrete slab or the redistributions between the steel web and the concrete flange, which significantly influence the overall load-bearing capacity of composite beams around a web opening. At present, knowledge of the complex load-carrying mechanisms of composite beams with web openings is limited, and essential aspects remain mostly unresolved [39].

In the framework of an ongoing FOSTA research project “Consistent design model for steel composite beams with web openings” funded by the AiF, experimental and numerical investigations are carried out to gain insights and ultimately to generate a design model for composite beams and floors with web openings. Due to this, local effects and the influence on the global load bearing behaviour combined with interaction of multiple openings are taken into account. The joint project is carried out by RPTU Kaiserslautern-Landau (department of steel construction) and RWTH Aachen University (Institute of Steel Construction and Institute of Structural Concrete).

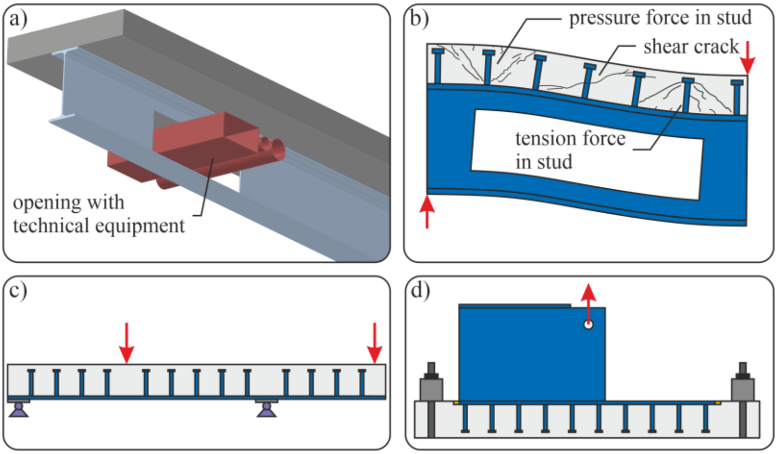

Fig. 3 a) Composite beam with opening and technical equipment, b) local effects in opening area, c) test setup assessing the shear force resistance of the concrete chord, d) test setup assessing the number of headed studs involved in load transfer in the opening area

The project comprises an extensive experimental and numerical program. Starting with the experimental investigation of local effects in and around single openings using small-scale tests, the individual effects are then combined in large-scale composite beam tests. The first goal of the small-scale test is to assess the shear force resistance of the concrete slab (Fig. 3c). In the undisturbed areas of the composite beam, the shear force is carried by the steel web that is cut out for an opening. The local forces have to be directed around the opening. Since the flanges do not have the required stiffness to carry shear forces, the shear force must be mainly dissipated via the concrete slab. Through these experiments, the influences of the headed studs, the steel web, and the width of the concrete slab on the shear force resistance are investigated, respectively. The other addressed effect in the second small-scale experiment is the number of headed studs responsible for the (tension-)load transfer in the area around the opening (Fig. 3d). Furthermore, the influence of openings on the global behaviour of composite beams is investigated. For this reason, the load-bearing behaviour of headed studs under combined tension and shear load is investigated. The results are then transferred to large-scale composite beams to examine the global behaviour. In the last step, the interaction of multiple openings in the steel web is investigated in several beam tests. The experimental investigations are accompanied by numerical simulations and parameter studies to develop design rules that can be eventually used on a European level in the Eurocode.

2.3 Composite dowels

Composite dowels enable rigid and high-strength connections between steel beams and concrete slabs. They consist of alternating steel and concrete dowels with different geometries such as puzzle or clothoid shapes. The development of these connections began with simple perforated steel plates, which were welded vertically onto double-T steel beams. Further experimental and numerical investigations over the past three decades have led to highly cost-effective composite dowels, which exhibit superior load-bearing behaviour compared to traditional shear connectors like headed studs (c.f. Section 1.1). Finally, general construction approvals have been granted in Germany to regulate this innovative construction method for shear connections of composite beams [4]. Currently, composite dowels are used under both static and cyclic loading. The accuracy and efficiency of design approaches still have room for improvement. Existing load reserves need to be identified to maximize utilization in design. While several studies have addressed key aspects of the load-bearing behaviour of composite dowels, such as combined shear and tensile capacity and the consideration of cracks in the concrete slab, there is still a lack of design approaches that accurately describe all relevant parameters [40–45]. The aim of the investigations carried out at the IMB is to enable the most efficient design of composite dowel bars under pure shear as well as combined shear and tensile loading by further developing existing design approaches and deriving new ones. Both static and cyclic load behaviour of the dowels will be addressed. In particular, the influence of concrete cracks in the concrete slab has to be examined to cover the design of the shear connection even in cracked concrete. This work involves numerous new experimental investigations and the evaluation of additional experiments from the literature, which provide a reliable foundation for achieving the aforementioned goal. The load-bearing behaviour of composite dowel bars is systematically examined using a variety of small-scale tests for different boundary conditions. Finally, the transferability of the results to components with realistic dimensions will be demonstrated through large-scale beam tests.

3 Conclusion

In conclusion, composite construction has proven to be an effective and versatile application in the construction industry, allowing for the optimal utilization of materials and load-bearing capacities. Its history dates to the 19th century, where combinations of concrete and steel were initially explored for fire resistance. However, the true potential of composite structures was not fully realized until the 20th century, when the connection of steel and concrete became the focus of research in various European countries. Today, composite construction finds applications in multi-storey buildings, infrastructural projects such as bridges, and even in sustainable wood applications.

The European standards for composite construction, represented by Eurocode 4, provide guidelines for the design and construction of composite structures. Efforts are ongoing to develop the next generation of Eurocode 4, addressing new challenges and advancements in the field. Research projects, such as those conducted at RWTH Aachen University, i.e., the Institute of Structural Concrete (IMB), focus on gaining insights on new construction materials used or developing optimized design rules for existing construction principles. Investigations aim to provide a technical specification for future developments in Eurocode 4, particularly concerning high-strength materials in composite columns. Another area of research explores composite beams with web openings, commonly used in multi-storey and industrial construction. Existing design standards do not fully address the complexities of these beams, leaving essential aspects unresolved. Ongoing research aims to gain insights and develop a comprehensive design model to account for local effects and the global load-bearing behaviour of composite beams with web openings. Furthermore, composite dowels are the subject of several investigations to generate a fundamental and holistic understanding. The ultimate goal is to create a foundation being used for future regulations on a European level.

Overall, continuous research and development in composite construction will further enhance its applicability and efficiency in the construction industry, meeting the demands of design, versatility, and resource efficiency in the future.

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