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Unbraced Composite Frames in Fire

Oliver Bahr

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Doktors der Ingenieurwissenschaften
genehmigte Dissertation*

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Abstract

Designers paid to date little attention to unbraced composite frames as structural system for buildings. There are two main reasons that hindered a more frequent application. First, normative regulations lack simplified methods for the fire design of unbraced composite frames. This can be attributed to their sway and the linked $P-\Delta$ -effects when subjected to fire, which complicates the design compared to non-sway structures. Second, it is demanding to construct external composite joints for the regarded one-bay frames. Thus, external joints are even in composite constructions mostly constructed as mere steel joints.

Nevertheless, unbraced composite frames offer important advantages. These include increased usable space and flexibility in the building's use, large spans, fast construction times, and inherent fire resistance. In this way, these frames are particularly interesting for one-bay office buildings with three storeys at most, where most building codes in Europe require a fire rating R60. To profit from their benefits and to gain a deeper understanding of fire-exposed unbraced composite frames, both experimental and numerical investigations were carried out in this thesis.

Overall, the load response of the joints is crucial for the fire performance of unbraced composite frames. Thus, new types of joints were developed. To achieve the fire rating R60 and to cover the expected large deformations in fire-exposed unbraced composite frames, the joints were thoroughly detailed. In this context, semi-rigid joints were important to limit moments in the joints resulting from restrained thermal expansion of the fire-exposed beam. In addition, it was shown that the reduced rigidity of the joints did not increase the sway of the frames significantly. Thus, it was more reasonable to accept limited sway of the frame instead of high local forces that are attracted by rigid joints. To limit the moment accordingly, the reinforcement bars in the slab were used as key component.

The feasibility of the design was verified by a test series that was conducted within the scope of the European project 'Unbraced Composite Structures in Fire' (UCoSiF). It comprised isolated joints tests at room and higher temperatures as well as two large-scale fire tests on frames. Overall, all tests confirmed the theoretical design of the joints and frames. Furthermore, the tests provided data for the validation of the established numerical models. As expected, the reinforcement bars bent around the column governed the load response of both the joints and the frames. In addition, the large measured rotations of the tested joints confirmed the effectiveness of simple constructional means to increase the rotational capacity. In addition, the fire tests on the joints proved that the fire rating R60 could be achieved even for high utilisation. Finally, the frame tests allowed for new insights in their load response under fire exposure.

To study the global response of the fire-exposed unbraced composite frames, a numerical model was established. Using a joint submodel, it was capable of considering the sequence of construction and load history in composite structures as well as the interaction of local forces of the column's part in the joint. The interaction was to date often neglected in the design of fire-exposed structures. However, it was very important for the external joints in unbraced frames since there is no surrounding structure where the forces can be introduced or coupled, where the first situation could be found in braced frames and the last at internal columns. In addition, the model also considered integrity failure of the vertical compartmentation. The validation of the numerical model against four isolated joint tests and two large-scale frame tests showed good to excellent agreement.

Thus, the numerical model was used to conduct parametric studies on fire-exposed unbraced composite frames. Overall, the studies underlined the importance of semi-rigid joints. Furthermore, fixed base supports as well as sufficiently stiff columns were crucial to achieve the fire rating R60. Based on the numerical results, a simplified method for the fire-design of unbraced composite frames was proposed. Its feasibility was exemplarily shown by comparison to results from the validated numerical model for fire-exposed unbraced composite frames.

Besides the global model, a detailed Finite Element model was established to study the local behaviour of one exemplary external semi-rigid composite joint. The validation against experimental data showed that the numerical model was capable of predicting both the temperature distribution in the joint and its load response. Results from conducted numerical studies confirmed the key role of the reinforcement bars bent around the column. It was additionally shown that the proposed design enabled the joints to cover large rotations.

Overall, the investigations showed that unbraced composite frames are a serious alternative to traditional load-bearing structures in low- and medium-rise buildings. In this work, the technical foundations were laid for an increased application of this type of construction.

Kurzfassung

Verschiebbliche Verbundrahmen wurden bislang als Tragstruktur von Gebäuden wenig verwendet, was zwei wesentliche Gründe hat. Erstens fehlen entsprechende vereinfachte Bemessungsverfahren für den Brandfall in den normativen Regelungen. Dies kann auf den seitlichen Drift der brandbeanspruchten Rahmen und den damit verbundenen Effekten nach Th.II.O. zurückgeführt werden, die eine Bemessung für den Brandfall gegenüber unverschiebblichen Strukturen erschweren. Zweitens ist die Konstruktion von Verbundbauanschlüssen für Randstützen technisch anspruchsvoll, so dass diese selbst in Verbundbaukonstruktionen häufig gelenkig ausgeführt werden.

Verschiebbliche Verbundrahmen bieten dennoch eine Reihe wichtiger Vorteile. Dazu gehören vergrößerter Nutzraum, erhöhte Flexibilität der Nutzung, große Spannweiten, schnelle Bauzeiten und integrierter Brandschutz. Insgesamt sind die Rahmen insbesondere für einfeldrige Bürogebäude mit höchstens drei Geschossen interessant, wofür die meisten Bauvorschriften in Europa eine Feuerwiderstandsklasse R60 verlangen. Um die Vorteile von Verbundrahmen nutzen zu können und ihr Tragverhalten unter Brandbeanspruchung besser zu verstehen, wurden sowohl experimentelle als auch numerische Untersuchungen durchgeführt.

Insgesamt ist das Tragverhalten der Knoten entscheidend für das Tragverhalten des gesamten Rahmens. Es wurden daher neue Verbundknoten entwickelt und sorgfältig detailliert, um die Feuerwiderstandsklasse R60 zu erreichen und die erwarteten großen Verformungen in brandbeanspruchten Verbundrahmen zu ermöglichen. In diesem Zusammenhang waren halbsteife Verbindungen wichtig, um das Biegemoment in den Knoten aufgrund der behinderten thermischen Dehnung des brandbeanspruchten Trägers zu begrenzen. Es wurde zusätzlich gezeigt, dass die verringerte Knotensteifigkeit die seitliche Verschieblichkeit des Rahmens unwesentlich beeinflusst. Demzufolge stellte es sich als vorteilhafter heraus, eine gewisse Verschieblichkeit des Rahmens zu akzeptieren und stattdessen große lokale Kräfte zu vermeiden, die durch steife Knoten angezogen werden. Die um die Stütze gelegte Deckenbewehrung war ein zentrales Element, um die Momententragfähigkeit des Knotens entsprechend anzupassen.

Um die Anwendbarkeit des Bemessungskonzeptes zu überprüfen, wurde im Rahmen des europäischen Forschungsvorhabens ‘Unbraced Composite Structures in Fire’ (UCoSiF) eine Reihe von Versuchen durchgeführt. Diese umfasste sowohl Verbundknotenversuche bei Raumtemperatur und unter Brandbeanspruchung als auch zwei großmaßstäbliche Brandversuche an Verbundrahmen. Insgesamt bestätigten alle Versuche das Bemessungskonzept für die Verbundknoten- und rahmen und bildeten die Grundlage für die Validierung der entwickelten numerischen Modelle. Die um die Stütze gelegte Deckenbewehrung bestimmte wie erwartet das Antwortverhalten sowohl der Verbundknoten als auch -rahmen. Durch das große Rotationsvermögen der getesteten Verbundknoten wurde zudem die Wirksamkeit einiger einfacher konstruktiver Maßnahmen bestätigt, um die Rotationskapazität zu erhöhen.

Darüberhinaus konnten die Verbundknoten in den Brandversuchen selbst bei hoher Ausnutzung die Feuerwiderstandsklasse R60 sicher erreichen. Schließlich ermöglichten die Rahmenversuche neue Einblicke in das Traglastverhalten bei Brandbeanspruchung.

Um das globale Tragverhalten von brandbeanspruchten Verbundrahmen analysieren zu können, wurde ein numerisches Modell erstellt. Mit Hilfe eines Untermodells konnte die Konstruktions- und Lastgeschichte für Verbundtragwerke simuliert werden. Zudem berücksichtigte das Modell die Interaktion von Schnittgrößen der Stütze im Bereich des Knotens. Diese Interaktion wurde bislang in der Bemessung von brandbeanspruchten Tragwerken häufig vernachlässigt. Für die verschieblichen Verbundrahmen war die Interaktion allerdings sehr wichtig, da die Schnittgrößen bei den betrachteten Anschlüssen an Randstützen weder an benachbarte Tragstrukturen noch über eine Kopplung der Kräfte, wie z. B. an Innenstützen, abgetragen werden konnten. Zudem berücksichtigte das numerische Modell den Verlust des vertikalen Raumabschlusses. Die Validierung an den vier Brandversuchen für Verbundknoten sowie den beiden Brandversuchen an den Rahmen ergab eine gute bis exzellente Übereinstimmung.

Das numerische Modell wurde für Parameterstudien an brandbeanspruchten verschieblichen Verbundrahmen verwendet. Insgesamt unterstrichen die numerischen Studien die Wichtigkeit der halbsteifen Verbindungen. Zudem ergab sich, dass die Einspannung der Stützenfüße sowie eine ausreichende Steifigkeit der Stützen von entscheidender Bedeutung sind, um die Feuerwiderstandsklasse R60 zu erzielen. Auf der Grundlage der numerischen Studien wurde ein vereinfachtes Bemessungsverfahren vorgeschlagen, dessen Anwendbarkeit exemplarisch an Hand der Ergebnisse des validierten numerischen Modells für brandbeanspruchte verschiebliche Verbundrahmen aufgezeigt wurde.

Ergänzend wurde zu dem globalen Modell für die Verbundrahmen ein lokales Modell für einen beispielhaften halbsteifen Verbundbauanschluss an Randstützen entwickelt. Die Validierung gegen Versuchsergebnisse ergab, dass das Modell sowohl die Temperaturverteilung im Verbundknoten als auch dessen Antwortverhalten gut simulieren konnte. Die Ergebnisse der durchgeführten Studien bestätigten die zentrale Rolle der um die Stütze gelegten Deckenbewehrung. Es wurde zudem nachgewiesen, dass der nach dem vorgeschlagenen Bemessungskonzept erstellte Verbundknoten eine große Rotationskapazität aufwies.

Insgesamt zeigten die Untersuchungen, dass verschiebliche Verbundrahmen eine Alternative zu bestehenden Tragstrukturen für niedrige bis mittelhohe Gebäude darstellen. In dieser Arbeit wurden wesentliche technische Voraussetzungen geschaffen, um diese Art von Tragstruktur vermehrt einzusetzen.

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Abbreviations

R60 Fire resistance time of 60 min exposure to ISO standard fire
R90 Fire resistance time of 90 min exposure to ISO standard fire
CFST column Concrete-filled steel tubular column
CFDST column Concrete-filled double skin steel tubular column
RHR heat release rate
IET Impulse Excitation Technique
STA Simultaneous Thermal Analysis
DTA Differential thermal analysis
RFDA Resonant Frequency and Damping Analyser
UCoSiF 'Unbraced Composite Structures in Fire'