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Strength of composite slabs with end anchorages. Part I: Analytical model

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ABSTRACT

An analytical model for predicting strength of composite slabs with end anchorages is presented. The composite slabs are considered as built-up sections of steel deck and concrete with partial interaction between them, which allows for the rational use of equilibrium and compatibility equations. The model is based on the consideration of flexural deformations of the slab and rotations of concrete blocks divided by the major crack, which is caused by the slip between the deck and concrete. The model directly accounts for end anchorage strength and flexibility, longitudinal shear strength, slab geometry, and properties of the deck and concrete. The model is capable of capturing effects of the slip on the stress–strain state of the slab and on the end anchorage strength mobilization. Recommendations for the determination of strength and flexibility of the end anchorages provided by welded shear stud connectors and mechanically attached shear transfer devices are presented. The model was verified against available test data and showed good agreement with the test results. It also demonstrated better prediction of composite slab strength when compared with other available design methods.

1. Introduction

Steel-deck-reinforced composite slabs are a primary method of floor construction in steel-framed buildings. The fact that the deck plays a triple role – serves as a working platform, a permanent formwork, and the slab positive reinforcement – makes the composite slabs one of the most economical options. For the deck to act as the positive external reinforcement, the composite action between the deck and concrete should be obtained by the means of mechanical interlock provided by embossments in the profile, frictional interlock provided by a re-entrant shape of the profile, end anchorages, or combinations of thereof. Composite slab end anchorages can be in the forms of shear stud connectors welded to flanges of steel beams through steel deck, mechanically attached shear transfer devices, or deformations of deck ribs at the ends of the sheeting. The welded shear studs, which main purpose is to ensure the composite action between steel beams and a cast-in-place concrete slab, are the most common slab end anchorages in steel-framed buildings.

Published results of several studies demonstrated beneficial effects of end anchorages on strength and behavior of composite slabs [1–8]. Porter and Greimann [1] tested eight composite slabs with end-span studs and seven control composite slabs without studs. The study showed that the end studs resulted in an increase of the slab strength by 8% to 33%, depending on span length and deck thickness. The failure mode of the studded slabs was tearing of the deck near the outer perimeter of the stud weld and slippage between the deck and concrete over the shear span length. This study revealed important information about behavior, strength, and failure mode of studded slabs and showed that the *m*–*k* method, which is typically used for slabs without end anchorages, can also be used for studded slabs. However, an analytical method for predicting a strength increase of the composite slabs due to the end anchorages was not developed. Therefore, a considerable number of tests needs to be carried out on studded slabs to determine their strength even when strength of identical slabs without shear studs is known.

The main objective of the study by Easterling and Young conducted at Virginia Tech and reported in [2,3] was to determine the effects of end-slip restraints provided by hot-rolled angles, cold-formed angles with and without lips, shear studs, and adjacent spans on strength of composite slabs and to develop an analytical method for determination of strength and initial stiffness of composite slabs. Six composite slab specimens were prepared and nine tests were performed. In five specimens, the deck was continuous over three spans, whereas one specimen was a single-span configuration. The study provided important information on strength of composite slabs constructed to simulate actual field conditions with respect to details at the intermediate and end supports. Obtained test data allowed the authors to conclude that strength of studded composite slabs can be calculated using traditional reinforced concrete analytical methods assuming that the entire steel-

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deck cross section yields at failure when sufficient end anchorage is provided. However, the magnitude of the force required for the sufficient anchorage was not precisely established. It was also pointed out that additional tests were needed to confirm the conclusion.

The first edition of SDI Composite Deck Design Handbook [9] published in 1991 was based on the Virginia Tech research [2,3] combined with data obtained in other studies. The handbook offered two design procedures: one for the slabs with welded end-span shear studs and the other for the slabs without shear studs. The design procedure for studded composite slabs accounted for the full composite action when the anchorage force provided by the actual number of studs was equal to or greater than the force needed to develop the full nominal moment and for the partial composite action when the anchorage force was not sufficient for the full nominal moment development.

Additional research was conducted at Virginia Tech [4] to obtain more test data to confirm the applicability of the reinforced concrete models to composite slabs and to refine the design rational of SDI Composite Deck Design Handbook [9]. Nineteen tests of the end and center spans were performed on eight three-span composite slab specimens. Results of the study confirmed that the reinforced concrete models can be used to determine strength of the composite slabs. The study also showed that strength of the slabs can be determined using a straight line interpolation between the studded and non-studded constructions when insufficient end anchorage is presented. The second edition of SDI Composite Deck Design Handbook [10] was produced based on this research. Equations developed based on the study are simple, convenient, and useful in the design of composite slabs. However, the required stud anchorage force is determined using a simplified equation that accounts only for deck yield strength, deck cross-sectional area, and cross-sectional areas of deck webs and bottom flanges. It does not account for other important slab characteristics that affect slab strength, such as longitudinal shear strength between the deck and concrete, deck height, and slab height. It will be shown later in the paper that the SDI method may overestimate strength of studded slabs with weak longitudinal shear strength between the deck and concrete or with no bond between them. End anchorage strength of welded shear stud connectors is determined in the SDI method using equations of the AISC Specification [11], which are based on the limit states of the stud failure or the failure of the concrete surrounding the stud despite the fact that several studies [1,5,6] showed that the failure mode for studded slabs was tearing of the deck near the outer perimeter of the stud weld. The end anchorage strength determined based on the limit state of steel sheet bearing against the stud is significantly smaller than the end anchorage strength determined based on the AISC Specification equations. As was shown in [4], the SDI method gave acceptable results for the tested slabs. However, the method being purely empirical may overestimate strength of the slabs with configurations not covered by the experimental program, which will be demonstrated further in the paper.

Jolly and Lawson [5] reported test results for six composite slabs, five of which had end anchorages in the forms of welded shear studs or mechanically attached shear transfer devices. Both non-embossed and embossed decks were used in the study. The slabs with end anchorages failed due to tensile rupture of the lower flange of the deck around shear connector, which is the same failure mode as the one observed by Porter and Greimann [1]. The authors noted that end anchorage strength may not be fully mobilized when longitudinal shear strength between the deck and concrete is reached because end anchorages are usually more flexible than relatively brittle longitudinal shear bond. Based on the test results, they proposed to combine 50% of the end anchorage capacity with the longitudinal shear capacity. The end anchorage capacity provided by welded shear studs was determined based on stud strength and strength of the concrete surrounding the stud, which is similar to the end anchorage strength determination used in [4,9,10]. Sheet bearing strength was not considered, despite the fact that the slab failure started with the failure of the sheet around the shear connectors. A simple design method was proposed. The method allowed a designer to determine a slab strength increase due to the end anchorage when strength of an identical slab without the end anchorage is known. However, the proposed method was based on a limited number of test results, and, therefore, its applicability to a wide range of composite slab configurations is questionable. This was confirmed by Chen, who reported that only 30% of the end anchorage strength or even less was mobilized in studded composite slabs tested in the study [8].

A calculation procedure to analyze composite slab behavior and strength was proposed by Daniels and Crisinel as an alternative to full-scale testing [6]. The procedure consisted of a nonlinear finite element model that accounted for the partial interaction between the deck and concrete. The model was capable of accounting for different span conditions, different end anchorage types, and additional positive and negative reinforcement. Longitudinal shear characteristics and end anchorage characteristics used in the model were determined from small-scale tests. The small-scale tests showed that the failure mode for both welded shear studs and mechanically attached shear transfer devices was deck buckling and tearing near the foot of the connectors, which corresponds to the observations made in [1,5]. The developed model was compared with test results in the companion paper [7], which also presented results of a parametric analysis performed using the model. The comparison showed that the calculation procedure gave reasonable and conservative predictions of the composite slab behavior and strength and was capable of capturing the end anchorage effects. However, despite the obvious advantages of the model for research and development, it is deemed to be too complicated for practical use.

Seven simply supported one-span composite slabs and two two-span continuous composite slabs were tested by Chen [8]. Studded composite slabs demonstrated higher capacity when compared with the slabs without studs. The method proposed in [5] was used to analyze test results, which showed that only 30% and less of the end anchorage capacity was mobilized in the test slabs. The obtained results imply that the reduction factor for the end anchorage capacity depends on the composite slab parameters not accounted by the Jolly and Lawson method [5].

Eurocode 4 [12] adopted two methods for the determination of longitudinal shear strength of composite slabs: the m–k method, which is similar to the empirical method given in ACSE 3-91 [13], and the partial shear connection (PSC) method. In contrast to the m–k method, the PSC method is based on a sound mechanical model and can be used to account for end anchorages. According to Eurocode 4 [12], resistance of a shear stud welded through the steel deck should be taken as the smaller of the shear resistance of the stud and the bearing resistance of the sheet, which is a function of the sheet thickness, stud diameter, yield strength of steel, and the end distance of the stud. Resistance of other types of end anchorages shall be determined from testing. It should be pointed out that Eurocode 4, in contrast to the other methods considered above, limits strength of welded shear studs by the bearing resistance of the steel sheet, which is in line with the failure mode observed in testing. However, the method assumes that the anchorage resistance can always be mobilized in composite slabs, which contradicts the test results reported in [5,8]. In addition, the PSC method is based on the assumption that stress in the entire deck section reaches yield strength at the ultimate limit state, which may not be always achieved especially in the slabs with the partial composite action. Finally, as will be shown in the paper, the formula for the sheet bearing resistance given in Eurocode 4 [12] appears to underestimate the end anchorage strength provided by welded shear studs.

The presented literature review showed that several design methods for determining the capacity of the composite slabs with end anchorages are available. However, the methods are either