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Innovative steel fibre reinforced composite slab systems

-Outline Report-

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Content

1. Introduction

1.1. Motivation of the research project

Conventional steel composite floors have proved themselves as an extremely cost-effective floor system for domestic, commercial and industrial buildings. Significant advantages arise from the low construction costs and especially from the benefit of saving time during the building process. In composite building construction the application of steel sheets keeping as long as possible and therewidth the use of continuous composite floors has been proved to be an eminent productive construction method (*Bode 1998*). Until now, numerous tests and research projects concerning the field of steel composite construction have been realised at the Kaiserslautern University of Technology. Amongst other, the load bearing behaviour of conventional reinforced continuous composite slabs was evaluated within the scope of a research group that was founded by the German Research Foundation (*Sauerborn 1995*). Based on these researches, the idea for further development emerged. The conventional reinforcement of continuous composite slabs should be reduced or rather substituted completely by the use of steel fibre reinforced concrete. By means of this substitution an enormous savings potential can be obtained. So, all operations concerning the conventional steel reinforcement can be omitted. Accordingly, the reinforcement detailing drawings as well as the control and the acceptance procedure, that mostly causes a delay, become superfluous. Furthermore the labour-intensive and time-consuming cutting and fixing of the reinforcing steel can be saved. Due to these omissions the construction method of steel fibre reinforced composite slabs allows an efficient progress of construction work. Depending on the floor area, an enormous time saving and therewith cost-savings are possible.

The use of steel fibre reinforced concrete as a load bearing element call for considerations concerning a raised safety level. In case of bad workmanship (e.g. undersized fibre content – or worst case – no fibre content over the intermediate support) a series of simply supported beams emerges and the steel sheeting keeps the slab in position. At this an adequate stability against collapse can be verified.

1.2. Purposes of the research project

Within the scope of the research project, one-way steel fibre reinforced composite slabs having been investigated. No conventional steel reinforcement have been applied: the hogging bending moment should be carried by the steel fibre reinforced concrete only. A steel fibre reinforced concrete composite cross section is not able to carry moments within the scale of a comparable conventional reinforced one. Therefore, steel fibre reinforced composite slabs possess a different load bearing behaviour in comparison to conventional composite slabs. The tests should offer valuable clues to the load bearing and deformation behaviour both in the serviceability and in the ultimate limit state. The results open out into a design procedure that provides a simple and safe design concept for the designing engineer.

The research project should afford a composite slab system that will be applied in practice as a competitive and innovative slab system. The tests should also provide the preconditions for building authority and technical approvals by individual cases.

2. Realisation of the research project

In order to investigate the load bearing and deformation behaviour of steel fibre reinforced composite slabs, tests on continuous as well as simple-span slabs were carried out. The production of the specimens and the accomplishment of the tests were executed at the laboratory of Kaiserslautern University of Technology.

Altogether, four different test series (series S1 to series S4) had been investigated. Table 2-1 gives an overview over the specimens and their dimensions. Thereby, the full-scale tests on steel fibre reinforced continuous composite slabs of series S2 represent the main tests.

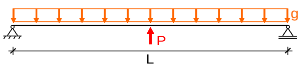
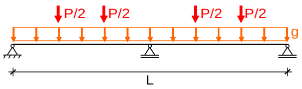
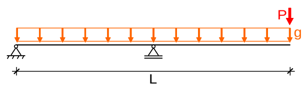
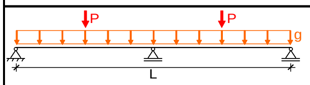
specimen		system	fibre type	length L [mm]	width [mm]	height [mm]	weight [kg]	sheet
	S1_SHR_51_V1	single-span	100 kg/m³ TABIX 1.3/50	2000	700	160	575	continuous
	S1_SHR_51_V2			2000	700	160	561	continuous
	S1_HODY_V1			2000	700	160	502	continuous
	S1_HODY_V2			2000	700	160	485	continuous
	S1_LEWIS_V1			1800	670	80	230	continuous
	S1_SHR_51_V3		60 kg/m³ HE+ 1.0/60	2000	700	160	561	continuous
	S2_SHR_51_V1	two-span		6000	700	160	1577	continuous
	S2_SHR_51_V2			6000	700	160	1541	continuous
	S2_HODY_V1			6000	700	160	1335	continuous
	S2_HODY_V2			6000	700	160	1348	continuous
	S3_SHR_51_V1	single-span	65 kg/m³ HFE 1.0/60	2000	700	160	500	continuous
	S3_SHR_51_V2			2000	700	120	413	continuous
	S3_SHR_51_V3			2000	700	200	704	continuous
	S3_SHR_51_V4			2000	700	160	502	jointed
	S4_LEWIS_V1	two-span	60 kg/m³ HE 0.75/35	2000	670	80	245	continuous
	S4_LEWIS_V2			2000	670	80	250	continuous
	S4_LEWIS_V3			2000	670	60	182	continuous
	S4_LEWIS_V4			2000	670	100	325	continuous

Table 2-1: Overview of the test program

For the tests different parameters varied. Thus profile sheets with trapezoidal as well as re-entrant geometry were applied. Furthermore differing slab heights and varied steel fibre reinforced concrete mixtures have been investigated.

For the calculation and design of steel fibre reinforced composite slabs the common design procedures of composite construction are picked up and modified. The load bearing ratio of the steel fibre reinforced concrete is implemented by the use of stress blocks. For the structural analysis design diagrams and tables are produced. The results of the experimental and analytical investigations open out into a design procedure. So a simple and safe analysis of steel fibre reinforced composite slabs can be made available.

3. Summary of the results

In Fig. 3-1 the load bearing behaviour of steel fibre reinforced continuous composite slabs is displayed exemplarily. Depending on the span and the fibre ratio, the moments in the serviceability limit state do not achieve the value of the crack moment yet (case ①). In this situation the slab is still uncracked. After increasing the load the crack moment M_{cr} is reached and the cross section is going to be cracked above the middle support (case ②). The level of hogging moment, which could have been arrived at, depends on the equivalent tension strength of the steel fibre reinforced concrete having made use of. Due to the fibre content, the moment can be kept approximately constant after cracking. This means that the load does not decrease after cracking. Rather a plastic hinge is formed at the middle support (1st. plastic hinge = 1.FG).

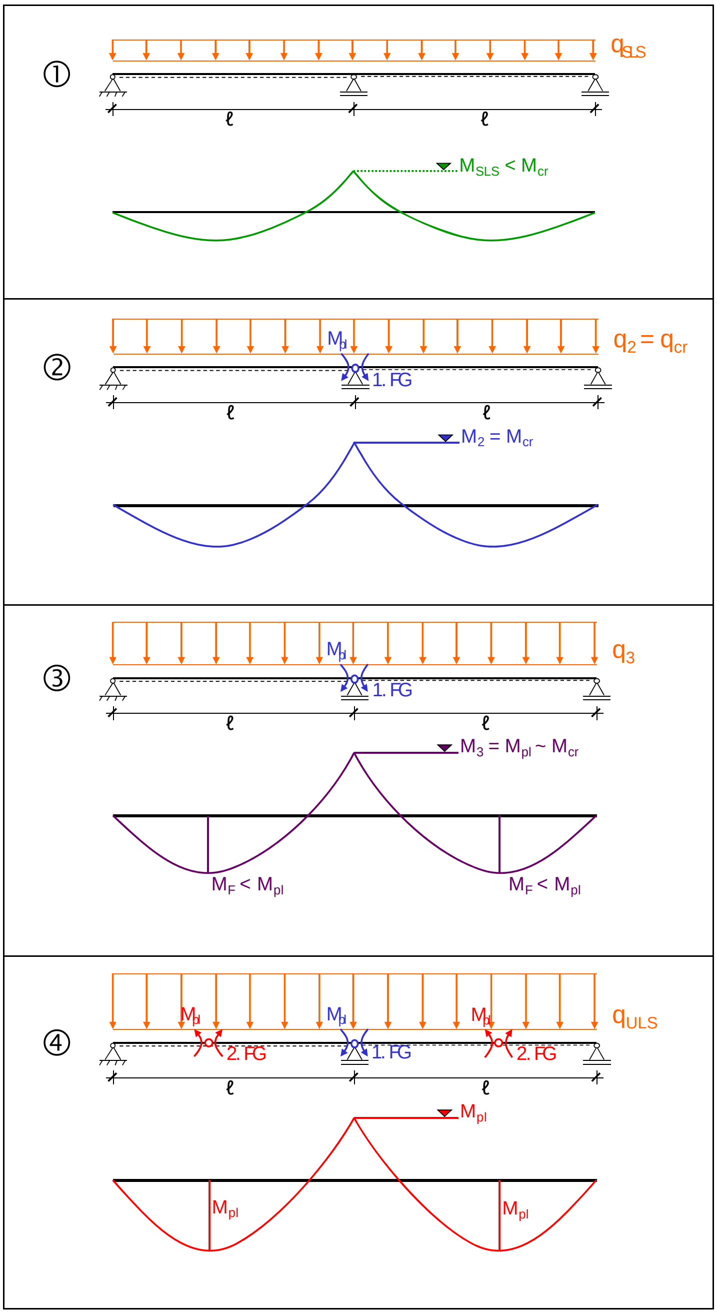


Fig. 3-1: Load bearing behaviour of steel fibre reinforced continuous composite slabs

With further load increase (case ③) the cross section rotates in the plastic hinge while the hogging moment can be kept constant on the value of M_{pl}. The hogging moments are redistributed to the span, whereby the sagging moments grow. The load can be increased further on (case ④) until the sagging moment resistance M_{pl} in the span is reached. Then a second plastic hinge is formed in the span (2nd plastic hinge = 2.FG). At this time a kinematic chain occurs and the system bearing resistance is exhausted. For the functionality of the system it is important to retain a sufficient rotation capacity of the plastic hinge at the middle support. All full scale tests on continuous composite slabs of series S2 show this load bearing behaviour. Fig. 3-2 displays the characteristic moment curves for one test of series S2. Here the described load bearing behaviour becomes apparent very obviously. The diagram depicts the curves of the hogging and sagging test moments.

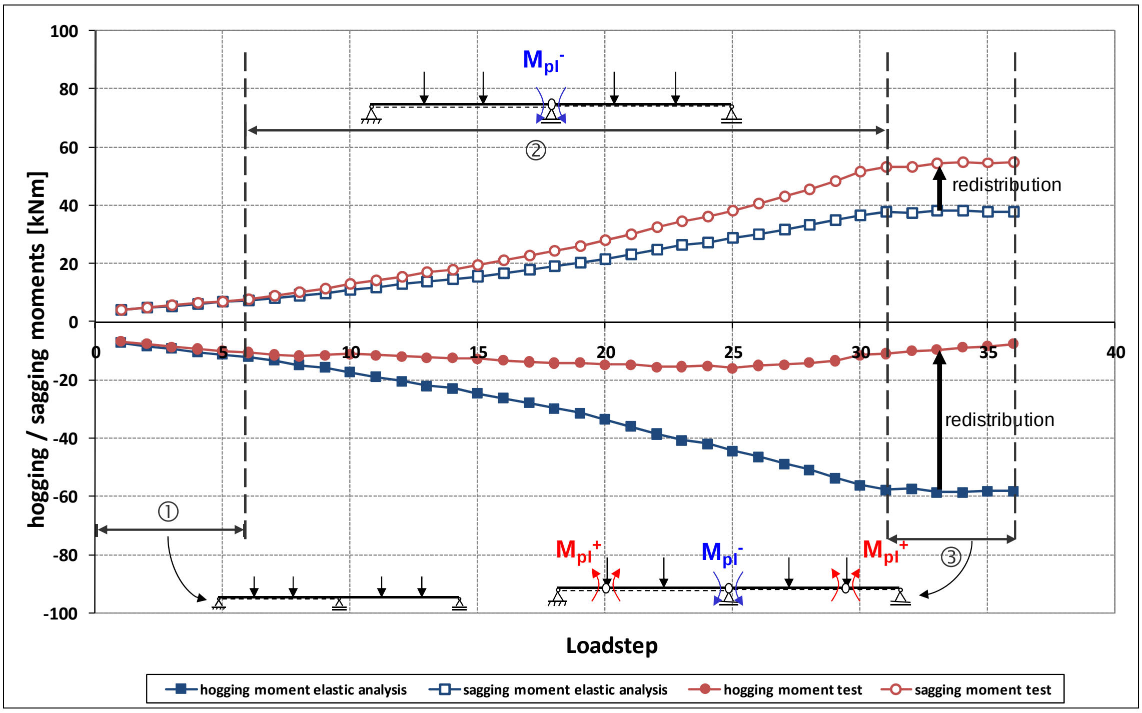


Fig. 3-2: Load bearing behaviour – exemplarily for one test of series S2

The experimental moments have been calculated by the use of the measured loads and support reactions. Furthermore, the elastic analysed moments are displayed. They have been calculated by the use of the measured loads and support reactions with the assumption of linear elastic behavior. In the range ① the slab is still uncracked. The experimental moments are conform to the elastic analysed ones. The load could be increased until the tensile strength of the concrete is reached. After cracking a plastic hinge (M_{pl}^{-}) with good rotation ability is formed at the middle support (range ②). The hogging moments could be kept approximately constant up to the failure of the slab, whereas the sagging moments are increased while raising the load. The hogging moments are redistributed to the span till the plastic sagging moment resistance (M_{pl}^{+}) is reached (range ③). Then a second plastic hinge is formed at the span and the system bearing resistance is exhausted. The redistribution of the hogging moments can be recognised in Fig. 3-2 very clearly.

The load bearing behaviour of steel fibre reinforced continuous composite slabs can be characterised as very ductile. The load could be increased as long as the system bearing resistance was reached due to the formation of a kinematic chain. After cracking the hogging moments of all tests could be still increased. This is a basic prerequisite for the securing of a ductile failure mode. Accordingly, the steel fibre reinforced concrete achieves the condition of a minimum reinforcement. In the area of the middle support multiple cracks emerge at all times, respectively in the region of the support boundaries. The crack propagation can be described as good-natured and ductile. The crack widths do not rise abruptly but continuously. With increased rotation at the middle support the fibres are going to be slowly pulled out of the matrix.

In order to estimate and analyse the load bearing resistance of steel fibre reinforced composite slabs, the common design procedures of composite construction (*DIN 18800-5 2007*) are picked up and supplemented with the load bearing ratio of the steel fibre reinforced concrete. In the tension zone the steel fibre reinforced concrete is considered by a stress block according to *DBV 2001*, the compression zone is also taken into account by a stress block according to *DIN 18800-5 2007*. The steel fibre reinforced concrete tensile-properties are determined by four point flexural bending tests according to *DBV 2001.* A scale factor α_{sys} and a factor for the long term behaviour α_c are also taken into account for the calculation. Due to the use of a stress block in the compression zone, the compressive strength of the concrete is reduced by a factor k_c of 0.8 according to *DASt 1994*. Fig. 3-3 displays the miscellaneous bearing ratios, which are accounted for the evaluation of the plastic negative bending resistance.

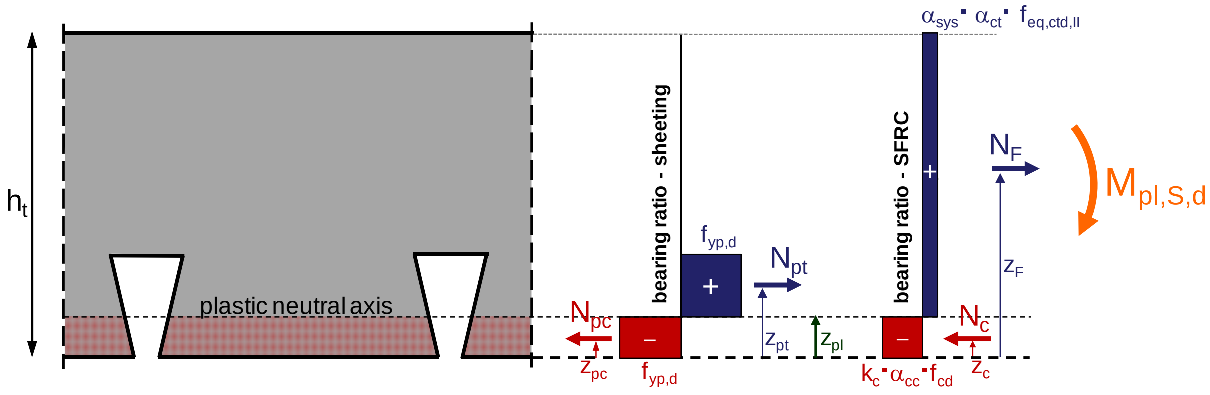


Fig. 3-3: Stress distribution for the calculation of the plastic moment resistance for negative bending

The location of the plastic neutral axis has to be destinated in an iterative procedure as long as the inner resultants achieve the equilibrium of forces. Then the plastic moment resistance can be calculated by forming the equilibrium of moments.

In most cases partial interaction only can be accomplished within the area of positive bending of composite slabs. So no full shear connection between the sheeting and the concrete topping can be realised. For the design according to *DIN 18800-5 2007* the partial interaction theory can be applied. The stress distribution for the evaluation of the plastic positive moment resistance concerning partial interaction is displayed in Fig. 3-4.

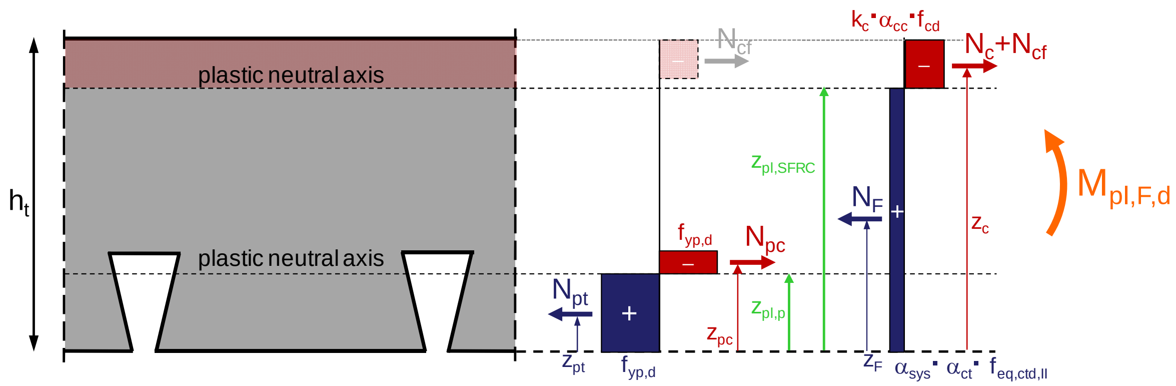


Fig. 3-4: Stress distribution for the calculation of the plastic moment resistance for positive bending concerning partial interaction

Due to the partial interaction, the sheeting is not drawn completely. The composite joint is able to carry the force N_{cf} only. There are two plastic neutral axes in the cross section, because the sheeting is charged with an additional loading by reason of bending. The location of the plastic neutral axis in the sheeting can be calculated concerning the condition that the tensile and compressive forces in the sheeting are in equilibrium with the force N_{cf}.

The load bearing ratios of the steel fibre reinforced concrete are also considered by the use of stress blocks. The location of the second plastic neutral axis interacts with the additional compressive force N_c that is effected by the steel fibre reinforced concrete and with the force N_{cf}. Using this stress distribution, all conditions from „no connection" to full connection can be described. So the partial interaction diagram that is needed for the static analysis can be evaluated following an iterative procedure.

The experimental tests were recalculated with the suggested analysis procedures. Thereby, their applicability becomes apparent. The bearing resistance of the tests could be estimated very well by the use of the figured stress distributions. In a parametric study design diagrams and tables are calculated for cases that are common in practice. Thereby, the compressive strength f_{ck}, the slab height h and the tensile strength of the steel fibre reinforced concrete had been varied as parameters. Likewise, it is very easy for the structural engineer to gather the bearing resistance out of the diagrams or tables pending on the respective edge conditions. Fig. 3-5 displays exemplarily a design diagram for a SUPERHOLORIB-slab [*Superholorib 2007*].

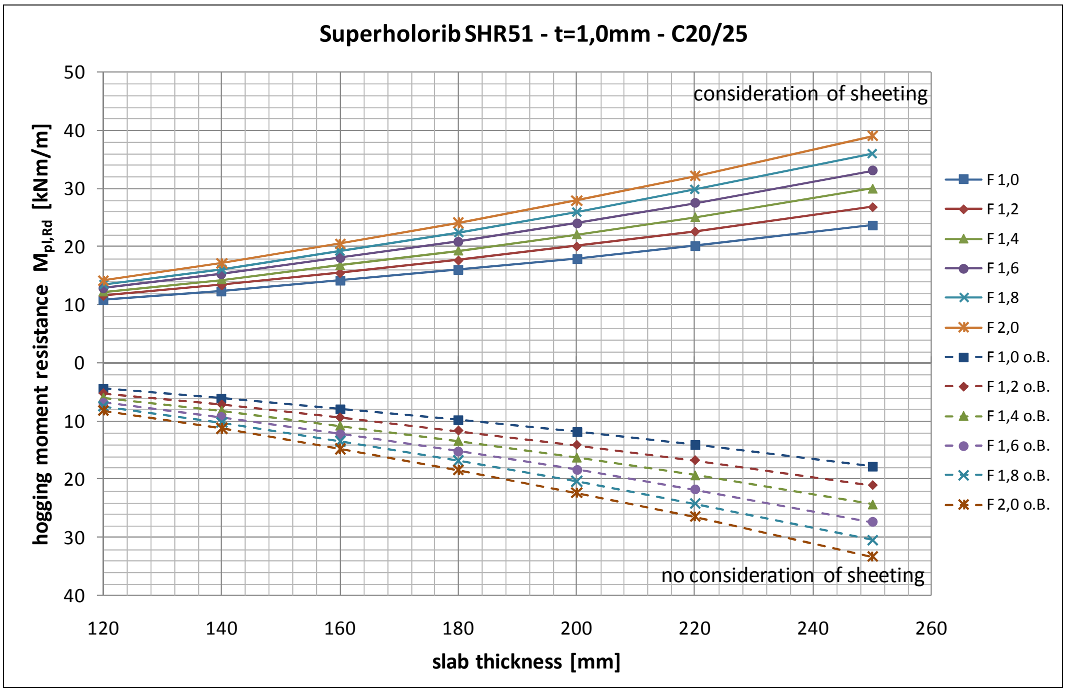


Fig. 3-5: Hogging moment resistance – SUPERHOLORIB SHR51 – t=1,0 mm – C20/25

The structural analysis of the positive moment resistance is carried out by the use of the partial interaction theory. Fig. 3-6 depicts exemplarily the partial interaction diagram for a SUPERHOLORIB-slab with a thickness of 160 mm.

Furthermore, design tables for the structural analysis of the shear force resistance were calculated. All single calculations had been bundled into design concepts. In the research project two different design concepts for the calculation of steel fibre reinforced composite slabs had been developed. As part of these concepts an additional design procedure has been incorporated that considers a complete breakdown of the fibres above the middle support. From this stage on a chain of simply supported slabs is going to occur and the sheeting keeps the slab in position. Thereby an adequate stability against collapse can be verified.

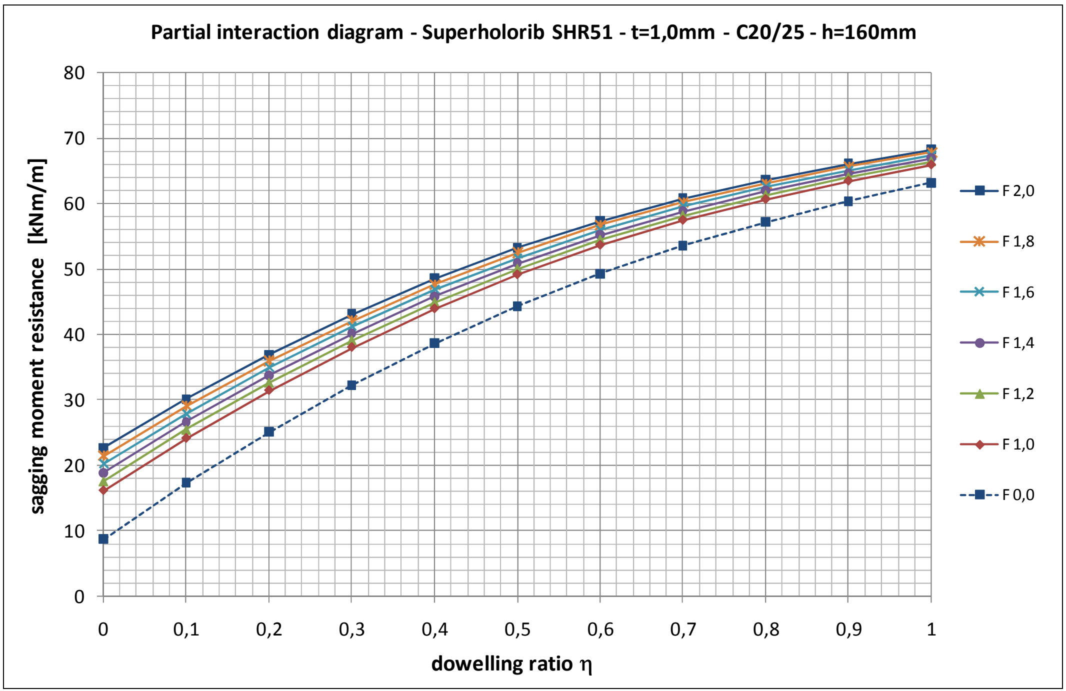


Fig. 3-6: Partial interaction diagram for SUPERHOLORIB SHR51 – t = 1,0 mm – C20/25

The first design concept #1 uses the elastic-plastic method for the structural analysis. The calculation of the stress resultants is carried out based on the linear elastic theory with moment redistribution (up to 30 %). The resistance of the cross section is analysed with plastic analysis. Steel composite slabs with a pure steel fibre reinforced topping only possess a low equivalent reinforcement ratio. Therefore the achievable span is limited. The parametric studies show that pure steel fibre reinforced composite slabs can be used for systems with a maximum span of five meters considering live loads that are common in domestic and commercial buildings. Whereas the required slab thickness for a span of five meters averages already 25 cm. Due to the required thickness, spans over five meters are uneconomical. For spans over five meters an additional steel reinforcement should be arranged across the intermediate support. For the calculation of the hogging moment resistance according Fig. 3-3 its load bearing ratio can be taken into account by the use of an additional force N_S (tension force of the reinforcement). Due to the relative low equivalent hogging reinforcement ratio and the limited moment redistribution, the load bearing resistance in the span cannot be exploited completely. Therefore the system possesses always a load bearing reserve which is an advantage in case of bad workmanship (e.g. undersized fibre content over the intermediate support). The continuously running steel fibre reinforced slabs contribute to a minimisation of the deflections in the span in comparison to a single-span system. For the practice oriented structural engineer the design concept #1 offers a safe and simple design method for steel fibre reinforced continuous composite slabs.

According to the second design concept #2 steel fibre reinforced continuous composite slabs are calculated using the plastic hinge theory (design method plastic-plastic). Hereby the partial interaction is taken into account. In addition to the plastic resistance of the cross section, the system bearing resistance can put profit on, too. In comparison to design concept #1 the slabs can here better be imposed upon. Within the research project, the tests on continuous steel fibre reinforced composite slabs using the profile types HODY [*Hody 2008*] and SUPERHOLORIB [*Superholorib 2007*] and a comparable steel fibre reinforced concrete demonstrate that the plastic hinge theory can be applied for systems with a maximum span of 3 meters. Thereby the moments were redistributed until a kinematic chain was formed. In case of larger spans the displacements and therewith the rotations at the intermediate support increase disproportionately high. This requires a large rotation that cannot be realised. In this case design concept #1 can be applied.

4. Conclusion

The researches having been carried on show that steel fibre reinforced continuous composite slabs constitute efficient slab systems for spans up to 5 meters. For the realisation of larger spans or local high loaded areas, an additional conventional hogging bending reinforcement can be arranged. Due to the omission of all operations concerning the reinforcement a considerable ease of work can be obtained that implicates to an enormous time-saving. Furthermore the use of composite construction and the substitution of the conventional reinforcement by the use of steel fibre reinforced concrete lead to a tremendous retrenchment of the required space on building site, which is a powerful advantage particularly for inner-city building areas. As a result of the earlier completion mainly for large floor areas a considerable economic benefit can be obtained.

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