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Large Span Floor Beams with Web Openings

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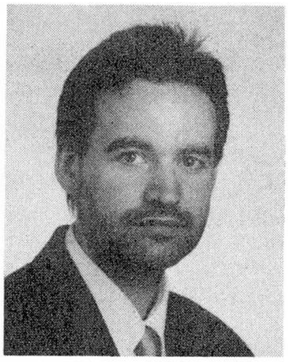

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Summary

To investigate the behaviour of a long-span floor beam, which is built-in in a high rise building, a full scale test was carried out at the University of Kaiserslautern. Besides other topics, the *different and large web openings* have been the particularity of this beam.

Physically nonlinear calculations show a quite good accordance to the behavior of the test specimen. For calculating the combined bending and shear capacity of the composite beam, a simple engineering model was developed. It is compared with the test results, which have been obtained from two other research projects, conducted at Kaiserslautern University.

In addition the vibrational behaviour of the same beam, which is built-in in a high rise building, is presented. The clear damping effect due to the completion of the building outfit, on the vibrational behaviour can be confirmed and quantified.

1 Introduction

In the past present in Germany buildings have been erected which used more and more the advantages of composite construction. By increasing the span of the composite beams, the number of columns can be reduced and the efficiency and economy of high rise as well as multistorey buildings can be increased. These long-span composite beams have some special aspects, which will be considered in the following:

- Composite beams have their major bending-resistance at midspan, whereas, according to elastic analyses, the largest bending moment firstly appears at the interior column. To yield profit of the bending-resistance at midspan a rotation-capacity of the beam (or the connection) at the interior support is necessary. This rotation-capacity depends on the geometry, the structural system, the construction and the loading
- Plastic analysis leads to an economical solution of the floor-beams. But the activating of the plastic bending moment at midspan and at the interior supports needs a certain rotation capacity of the plastic hinge sections

- Because of the high bending moments and the high resistance, the web openings become more and more critical with regard to deflection and stresses particularly under large transverse shearing forces
- The reduction of the self-weight gets important with increasing span of the composite beam and the number of storeys of the building. A solution could be to use light weight concrete and high strenth material for the steel beams
- The importance of crack-width-control increases by considering these points, especially if the structure is designed plastically

At the University of Kaiserslautern we have made large-scale-testings especially to have a view at these, above-mentioned points. In the following, we have a close look on *one* long span beam test with large web openings:

In January 1995 a *full scale test* of a composite beam containing large web openings was carried out. The composite beam and test setup is shown in Fig. 1 and can be characterized by the following features:

- full scale specimen, very similar to the beams used in the Commerzbank building;
- welded and tapered steel beams made of Fe 510 (= S355; 510 N/mm² tensile strength);
- large rectangular and 2 circular web openings;
- the slab consists of "light" normal concrete LB 35 (C 35/45) with density r = 1.99 kN/m³ (light weight aggregates "Lipor");
- profiled steel sheeting "Super-Holorib" with embossments, but without any end anchorage means (the ribs were oriented transversely to the beam);

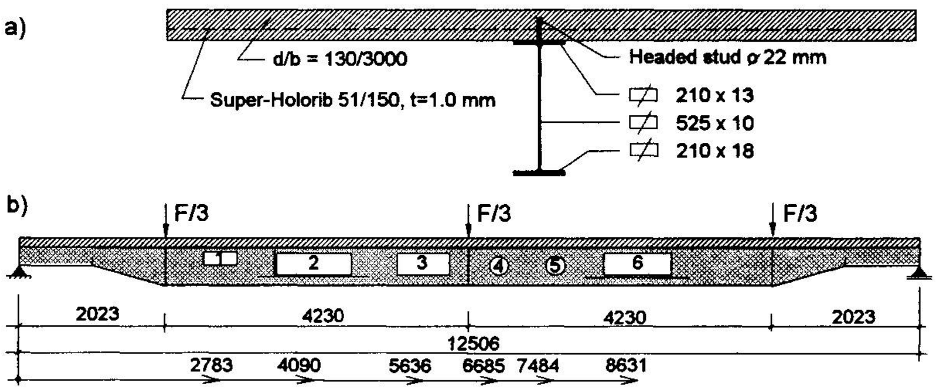

Fig. 1: Test specimen and setup a) cross-section b) elevation

- the sheeting is used in order to serve as shuttering during concreting and as lower reinforcement in the final composite stage, resisting the tensile forces from transverse bending and longitudinal shear;
- shear connection by one headed stud ø 22 mm per rib, as it is the normal practice in Germany. The studs were not throughwelded but welded in the shop. The steel sheets were holed at these points;
- transverse bending was applied using additional jacks independently from the beam cylinder force;
- openings with a minimum number of stiffeners and partly close arranged to each other, thus influencing each other (Vierendeel-action).

Any instability problems, such as local buckling, were not taken into account. But separate calculations have been carried out to ensure that the beams have an adequate margin of safety against buckling, and this is, of course, necessary in any case.

2 Test Performance

Figure 1 shows test specimen and test setup including the test loading by spreader beams under a hydraulic jack.

Measurements were taken by strain gauges on the steel beam, on the reinforcement and on the stud shear connectors. In addition vertical as well as relative displacements at the steel-concrete interface were measured.

The overall behavior can be seen from Fig. 2, where the cylinder load $F = F_{cyl}$ is plotted against deflections at mid span of the composite beam. The behavior can be characterized by a linear elastic relationship from the beginning of loading up to a cylinder load near to the design resistance level (ULS). The loading was further increased step by step, and yielding occurred in the steel beam under the inner web openings, mainly at the unstiffened rectangular opening No. 3. This yielding results in a reduction of stiffness at a cylinder load of $F_{cyl} \cong 550$ kN. The remaining branch indicates yielding with strain hardening, accompanied by large deformations of the composite beam.

- At the end the beam test was stopped at a maximum mid span deflection of $w \cong 350$ mm ($\triangleq L/35$) without any brittle failure in the concrete slab. Furthermore no instability problems such as local or lateral buckling near the free edges of the openings were observed during this test.
- The slip at the steel-concrete interface was small (< 0.9 mm at ULS), and the shear connection was not decisive for the resistance of the beam tested (full connection).
- The cylinder load $F_{cyl} \cong 226$ kN plus dead weight of the specimen and load spreader beams corresponds to the loading under service conditions (SLS in Fig. 2). In the test the maximum deflection at this load level was $w = 18.7$ mm ($\triangleq L/670$).
- The natural frequency of the composite beam was measured, and the value of the first natural frequency $f_0 = 6.2$ Hz was indicated.

3 Nonlinear Calculations

In the nonlinear analysis the yield criterion of von Mises, associated with Prandtl-Reuss equations including kinematic strain hardening, has been used for structural steel. The concrete material model predicts the failure of brittle materials. Both cracking and crushing failure modes are accounted for. The concrete is isotropic before cracking, and after cracking a smeared-cracking model is used. It is assumed that concrete becomes orthotropic after first cracking has occurred. The failure surface of concrete is defined according to [7]. The shear connectors are represented by P-δ curves from push out tests, but without transverse bending in the slab.

4 Comparison Between Test-Results and Nonlinear Calculations

Fig. 2 shows the global load-deflection behavior at mid span and contains the comparison between measured and calculated values: the accordance is quite good, but the calculated beam behaves a little bit stiffer than that tested. (The horizontal lines in the diagram mark the load which can be carried according to the engineering model (see chapter 5.) For the differences the following reasons may apply:

- Residual stresses due to the welding process were not taken into account.

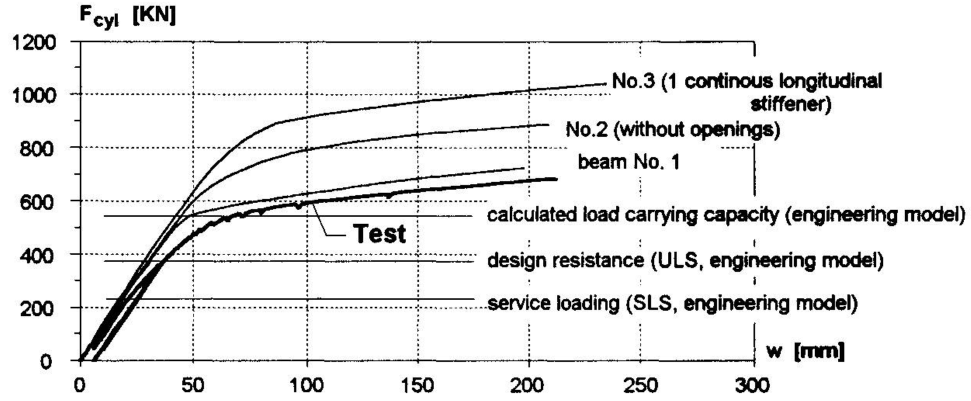

Fig.2 Global load-deflection behaviour

- Because of the absence of a realistic stress-strain relationship for the "light" normal weight concrete, it was approximated.
- The P-δ curve for studs embedded in concrete with light aggregates (LIPOR) and subjected to transverse bending was assessed.
- Creep and shrinkage effects have been neglected. The fact, that the steel beam had to support a certain amount of the dead weight during concreting, was not considered.
- Local as well as lateral buckling and imperfections may have reduced the local stiffness of the beam, though such effects have not been observed in the test at all.
- The composite beam has been modeled by a large number of finite elements, but the mesh should be further condensed, to make allowance for more deformations around the openings.
- The load cycles have not been taken into consideration.

A lot of very interesting results can be achieved by means of ANSYS, so for example slip and connector forces over the whole beam length, see Fig. 3.

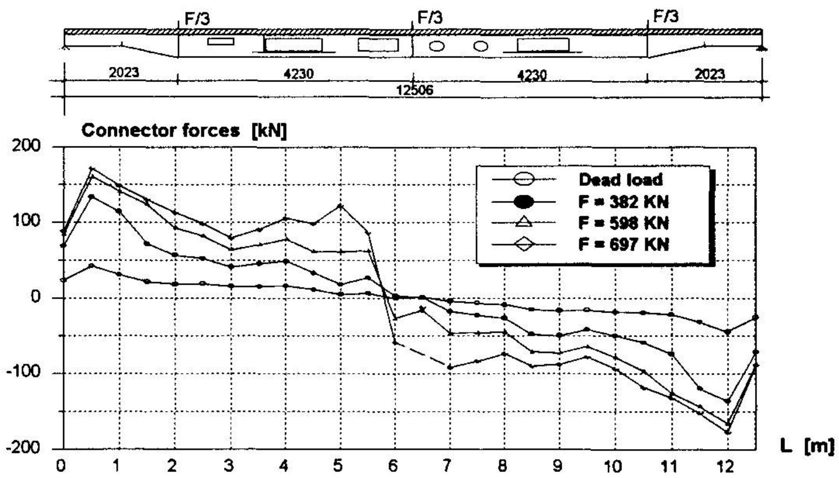

Fig. 3 Connector forces in the composite beam

- It can be seen, that the distribution of the connector forces follows the elastically calculated shear flow, as far as the loading is small.

- In the second, post-yielding phase with strain hardening, the openings as well as the plastic beam deformations near mid span effect the behaviour obviously. But the shear connection is not decisive for the ultimate beam strength, because slip and connector forces are limited to values far below the ultimate values.
- The deflection of beam No. 1 with web openings is only 1.1 mm or 3.5 % larger than that of beam No. 2 without openings. Beam No. 3 with openings and one continuous longitudinal stiffener has about 10 % more stiffness.
- The natural frequencies differ by not more than 1.6 or 4.8 %, respectively.

5 Calculation Model (Engineering Model)

To detail beams with large web openings aimed at a minimum number of stiffeners is a design problem that arises not only in case of composite construction.

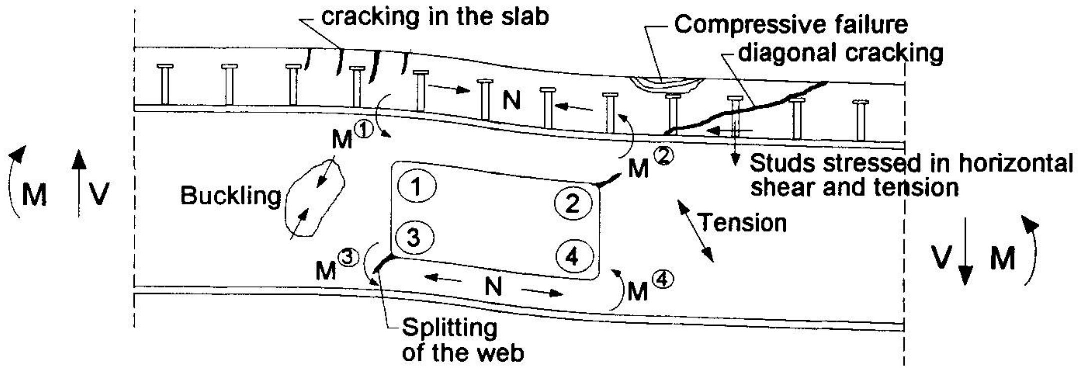

Fig. 4 Deformation at opening No. 3, engineering model

To develop a calculation model for bending and particularly for vertical shearing forces two research projects have been carried out at Kaiserslautern University [4],[5].

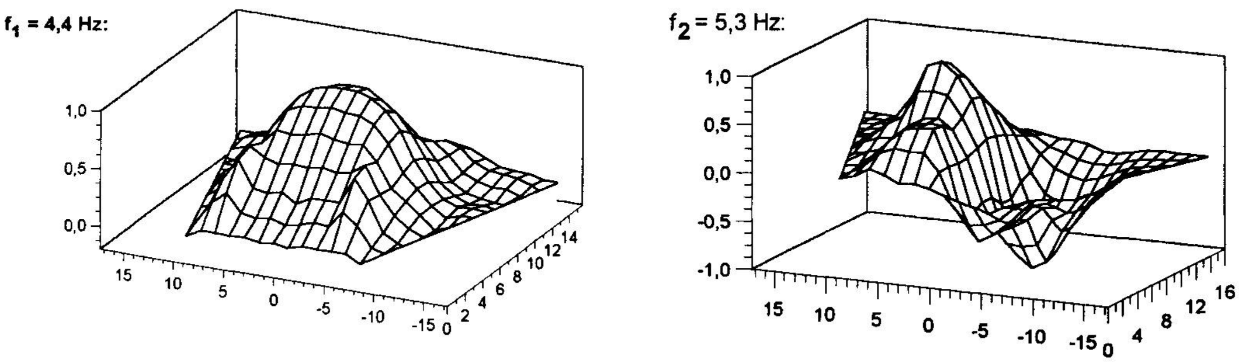

Fig. 5 First two shapes of the maximum acceleration of the slab

To determine the parameters of the engineering model, that is based on the usual beam theory, more than 44 tests from our projects and other researchers were recalculated [4],[5],[6]. The accordance between the test-results and analysed results is quite good (mean value 0.981, standard deviation 0.066).

6 Vibrational Behaviour

The tested beam also is member of a composite floor in a high rise building in Frankfurt/Germany.

Therefore it also was possible to make various measurements of the vibrational behaviour of the beam which is built-in in a real slab construction. To assess the results of the measurement it can be said, that

- the agreement between the calculated and measured natural frequency has been quite good: 4.27 Hz to 4.4 Hz.
- the corresponding shapes (to f = 4.4 Hz and f = 5.3 Hz) are given in Fig. 5.

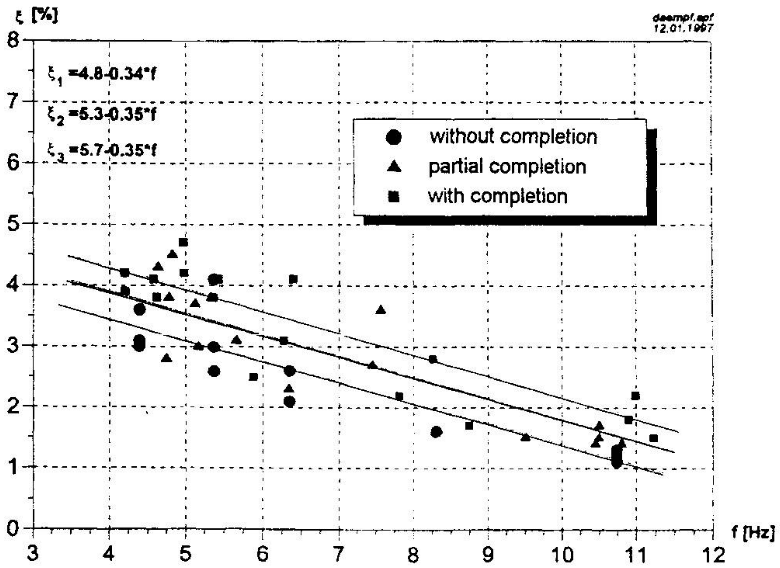

Fig. 6 Damping effect in relation to the frequency and completion of the interior fitting

- according to Bachmann [3] the lowest vertical acceleration which can be perceived is 0.034 m/s². The maximum measured acceleration is 0.02 m/s² (with completion of the interior fitting); a reduction of the comfort can surely be excluded.
- the clear damping effect of the completion of the interior fitting as suspended ceilings and partitions is shown in Fig. 6. The average damping at the frequency of 4.4 Hz is about 4 %.

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