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Summary of doctoral dissertation: *„Fatigue strength of steel dowels in innovative shear connection of steel - concrete composite beam."*

Steel-concrete composite structures are formed by an appropriate connection between steel structural members and concrete. The connection allows the collaboration of the structural members and thus – more effective use of strength parameters of the materials. Most often the composite behavior occurs through mechanical connection realized by means of the separated connectors. The fundamental problem of these solutions was the prefabrication stage of steel composite beams that is the assembly of the connectors that was very time-consuming and labor-intensive. Furthermore, steel beams had to have I-shaped cross-section which increased the consumption of the steel beam. Innovative shear connection of steel-concrete composite beam allowed to reduce the time of steel beams assembly and thereby reduce the costs of the prefabrication. The essence of the innovative shear connection is cutting web of the steel rolled beam in such way that obtained dowels in each part, after concreting them in the slab, would form a type of mechanical connector allowing transmission of delamination forces between steel and concrete. Delamination forces undergo changes in each dowel and are transmitted by direct bearing of concrete on the front surface of the dowel and by adhesive forces between flat surfaces of the steel beam and concrete.

The shape of cutting the dowel was repeatedly modified and optimized. The latest shape is marked in Europe as MCL and it combines many advantages of the previous shapes.

Curvilinear edge of the MCL dowel is a geometrical notch that reduces fatigue strength of the steel beam. Depending on the thickness of the concrete part, the dowels may work in the tensile stresses cross-section. It is dangerous in case of cyclic loadings because during initiation of the fatigue crack, the crack may propagate up to the loss of the bearing capacity of the entire steel beam section. This problem did not occur in the solutions with separated connectors, such as bolts, where propagating crack could stop when it achieved the level of the compression zone in the web.

Fatigue analysis of the structure with the innovative shear connection is complicated due to unusual stress state of the steel dowels that can vary with the number of cycles or with the appearance of the crack in the dowel. Quality of the frontal surface of the dowels that depends on cutting technology can also affect the fatigue strength. These issues complicate research on fatigue strength of the MLC dowels which, so far, have not been carried out.

The doctoral dissertation proposes the theses that have been proved experimentally, numerically and analytically:

1. Technology of cutting steel dowels in the innovative shear connection can affect the fatigue strength of the connector.
2. There are two possible mechanisms of the fatigue damage of the MCL-type connector in the innovative shear connection of the steel-concrete composite beam: tearing of steel flange and pulling out of steel dowel.
3. Pulling out of the steel dowel of MCL-type is caused by formation and propagation of the second crack in its upper part, on the opposite side of the first crack.

Two independent experimental studies were carried out in order to realize the aims of the dissertation. The first one was the cyclic study on paddle-shaped samples, cut with three different cutting technologies: oxygen-acetylene gas cutting, plasma cutting and water cutting. The obtained results indicated the possibility of influence of the cutting technology of innovative shear connectors on their fatigue strength. The connectors cut with the oxygen-acetylene gas cutting technology may have a greater fatigue strength compared to the two other technologies – plasma and water cutting. This conclusion proved the first thesis presented in the dissertation. In studies attention was paid to the quality of the cut surface of the samples. For selected samples measurements of surface roughness of these surfaces were carried out as well as macroscopic and microscopic examinations of the material in area of fatigue cracks. The obtained results, compared with results of other studies on the influence of surface roughness on the fatigue strength of the samples, showed that the influence of cutting technology of the shear connector in the steel strip may be greater than the influence of cut surface condition. The results of the studies suggest that the literature database should be supplemented by a factor affecting the fatigue strength of the structure, that is the impact of the cutting technology which has not yet been described. Evaluation of the influence of the cutting technology requires further experimental studies carried out on the larger number of samples. The results of the performed studies should be treated as preliminary. However, they are important from the point of view of selection of the cutting technology of the innovative MCL-type connectors for further, principal studies on composite beams.

The second cyclic study was carried out for the composite beams with an innovative strip shear connection of MCL type. Due to complex geometry of the beam section and different values of the resistance and modulus of elasticity of the used materials, the beams scale was close to the natural scale. On the one hand it helped eliminate the influence of the scale effect on the obtained results, on the other hand it required specialist equipment to produce large excitations. The test were carried out on two beam types with different web heights of the steel parts of the section in order to obtain different positions of the center of gravity of the steel section regarding the axis of gravity of the composite cross-section. The aim was to obtain different values of the delamination forces in the dowels. Two beams were tested – one with the so-called high web and one with the so-called low web. The lack of possibility to observe fatigue cracks of the steel dowels complicated the research, therefore the beams with so-called 'high web' were provided with observation channels. These were pieces of steel tubes punctually welded to the steel strip. Through these channels, using a thermal imaging camera, the observation of fatigue cracks growth was made. In addition, in the studies electro-resistant and inductive sensors were used for measurements of, inter alia, deformations of steel dowels and composite beam deflections.

The results obtained from strain gauges stuck on steel beams showed that to the moment of the fatigue crack appearance in the steel MCL-type connector or to the moment when it reaches its limit value the strain variation in the critical point of the steel dowel was almost constant with the increasing number of loading cycles. Therefore, for uncracked beams as well as for the cracked beams when the crack length does not exceed a certain value, stress state within the steel dowel is almost constant. If the stress state in the beam without fatigue cracks changed with successive loadings, the existing procedures of the bearing capacity of steel dowels could be more complicated.

Experimental studies of the composite beams proved that the fatigue durability of the MCL-type steel connectors is larger than durability of the PZ-type steel connectors, often used in civil engineering before the development of the MCL shape.

After cutting and forging of the tested beams, two mechanisms of fatigue damage of the MCL-type steel connectors were observed, caused by propagation of cracks: tearing of steel flange and pulling out of steel dowel, which proves the second thesis. Most often the cracks appeared in the upper and lower geometrical notches where the concentrations of the main tensile stresses occurred. The crack initiation in the upper geometrical notch showed fixing of the dowel in the concrete part. Both points of fatigue cracks appearance and propagation angles were confirmed in numerical analyses of beam models. It should be noted that other factors, such as micro cavities on the shape-cutting surface or material nonlinearity of steel, could have affected propagation direction. These factors cannot be included in calculation model.

The process of the crack growth in damage model, as a result of pulling out the dowel where the main crack propagating in the direction of a steel flange changed its direction resulting in pulling out of the dowel, was subjected to a detailed analysis. Numerical calculations of cracks in single dowel and for all loaded dowels were carried out in stages.

The cracks were modeled in the points of the maximum tensile stresses with the propagation directions and maximum lengths measured in the experimental test. It was noted that the crack initiation in the upper back part of the dowel occurred when the main crack length on the other side of the dowel in the lower notch did not exceed a certain limit value. When the two cracks achieved certain length values the main tensile stress trajectory in the steel dowel was clearly changed. The crack in the lower notch underwent curving that leaded to pulling out of the steel dowel. That conclusion proved the veracity of the third thesis. Process of initiation and propagation of the cracks in a steel dowel was divided into three stages, taking into account the interaction of two fatigue cracks. A shape of a propagation curve for the main crack (in lower geometrical notch), which development stages were different from the cracks observed in steel structures, was proposed. In the case of analyzed steel dowel breaking a phase of so-called brittle fracture did not occur. That phenomenon was confirmed also in metallographic tests of fatigue fractures.

Analytical calculation of steel dowel crack propagation were carried out in the dissertation. Obtained results were significantly lower than values measured in the experimental tests and depended mainly on the assumed values of the crack growth in successive stages of the propagation. It should be noted that in case of composite structures the influence of concrete surrounding steel dowels may be significant but is still not recognized. The analytical formulas by which the calculations were performed were based on cyclic studies carried out for steel elements.

The behavior of the steel connector in innovative shear connection of the composite steel-concrete beam is complex in terms of fatigue strength. It depends on a complex stress state at the interface between steel and concrete, which on the other hand changes with the propagation of cracks and with the apparition of the separate crack in the steel dowel. In the future elaboration fatigue tests should be considered that would ensure, besides the correct stresses in the steel dowels, a possibility of constant observation of the steel dowels during loading.