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DESIGN OF BEAM-TO-BEAM BUTT-PLATE JOINTS IN COMPOSITE BRIDGES

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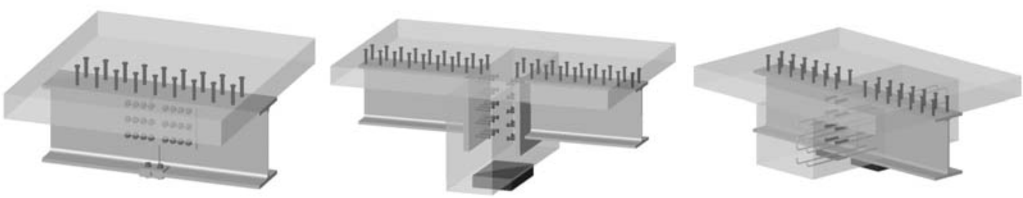
***Abstract**. This paper presents an analytical design method for beam-to-beam butt-plate joints connected with studs to a concrete transverse deep beam for composite bridges. The proposed design method is an elastic model at the ultimate limit state, mainly based on the Eurocodes and also on the data obtained from experimental and numerical investigations carried out at the Laboratory of Structural Mechanics at INSA-Rennes.*

1 INTRODUCTION



Bolted joint with web cover-plates and a direct contact between bottom flanges | **Butt-plate joint** | **Embedded joint**

Figure 1: Beam-to-beam joint solutions

In order to promote new composite techniques for bridges of small and medium spans, innovative solutions have been investigated for the design and the fabrication of beam-to-beam joints. In Europe, several projects have been carried out on this subject the past ten years [1]. More recently, in France, taking benefit of a National Research Project (MIKTI), the Laboratory of Structural Mechanics at INSA in Rennes has undertaken research works to find new types of beam-to-beam joint ensuring the continuity of composite beam in bridges. New joint solutions have been selected (figure 1) with the aim to find economic solutions [2] using, if possible, standardized or ordinary prefabricated elements easily mounted on site by a same builder with a minimum of construction operations and without any sophisticated technology (as outdoor welding for example). Analytical methods have been developed for these new joints.

This paper presents the analytical design method of a beam-to-beam joint realised with butt-plates connected with studs to a reinforced concrete transverse deep beam (figure 1).

2 EXPERIMENTAL AND NUMERICAL RESULTS

The specimen tested at the Laboratory of Structural Mechanics (INSA of Rennes) is presented in figure 2. A concrete block (which represents the concrete transverse beam) at mid-length of the specimen is supported on a bearing. The specimen is loaded at its two ends by two hydraulic actuators. On each

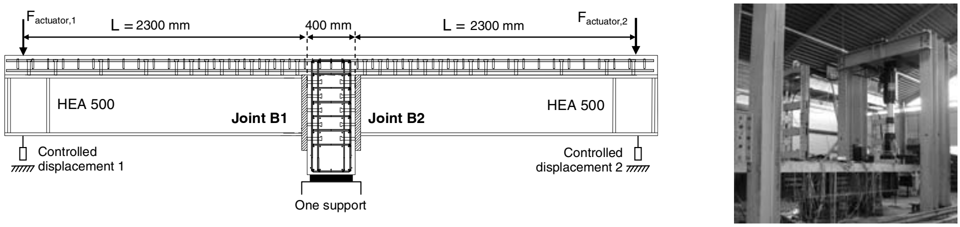


Figure 2: Tested specimen and experimental setup

side of the concrete block, end steel girders are connected by butt-plates whose dimensions are 600×500×45 and 24 studs (d = 22mm and h = 125mm) uniformly distributed on each butt-plate (4 lines and 6 rows of studs). On the right side (joint B2), the butt-plate was welded with the steel beam with a fillet weld and on the left side (joint B1) a full penetration butt weld was used. Main common details of the composite beam are HEA 500 (S355) steel cross-section (E_a = 200 000 MPa, $f_{y,a}$ (web) = 450 MPa, $f_{y,a}$ (flange) = 420 MPa), concrete slab (C45/50) whose dimensions are b^{-}_{eff} = 1600mm and h_a = 160mm with 1.26% percentage of longitudinal reinforcement (2 layers of 8 bars of 16mm diameter - S500), full shear connected (2 lines of 12 welded headed studs per span ; d = 22 mm, h = 125 mm, E_a = 200 000 MPa, f_y = 450 MPa). In the connected zone, the percentage of longitudinal reinforcement is increased to 2.67% (9 additional bars d_b = 16 mm - S500 of length $b_{eff} + \ell_{bd}$ = 2050mm) and the number of connectors is doubled (24 studs on the same length). The tested specimen has been equipped with 80 strain gauges and 40 transducers. The principal of experimental setup is indicated in Figure 2. Two types of loading procedure have been exerted: firstly a fatigue loading under a high range of bending moment to obtain significant information about the fatigue resistance of some details of the joint and the shear connection and secondly a monotonous increase of actuator loads towards the specimen collapse.

Figures 3 shows the moment-rotation curve where rotations are those defined between the cross-section at mid-joint and the beam cross-section immediately adjacent to the joint on each side. Rotations are deduced from inclinometers, beam deflections and relative linear displacements measured over the whole depth of the joint. Bending moments are calculated from the measured actuator loads multiplied by the appropriate lever arm L (figure 2).

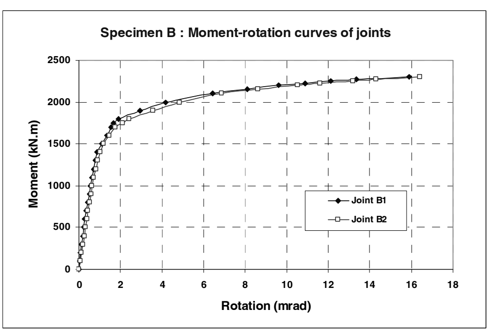


Figure 3: Moment-rotation curves

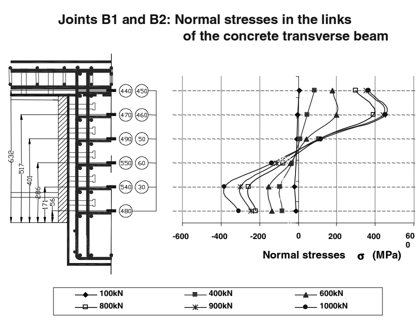


Figure 4: Normal stresses in the horizontal links on the width of the concrete block

Main joint moment-rotation characteristics measured from the above curves for both joints B1 and B2 are: an initial rotational stiffness $S^{exp}_{j,ini}$ = 1986 kN.m/rad, a maximum exerted moment $M^{max}_{exerted}$ = 2300 kN.m and a rotational capacity greater than 16 mrad. Compared to the calculated initial rotational stiffness (under flexural bending) $S_{eq} = EI_2/\ell = 210000 \times 140558 \times 10^4/250 = 1180$ kN.m/mrad and the elastic resistance moment $M_{el,b,R}$ = 1842 kN.m of an equivalent composite beam section having the same length of about 250 mm (as the one used to define the joint rotation); Joints B1 and B2 appear fully efficient in stiffness and strength.

Figure 4 gives the distribution of the normal stresses in the horizontal links on the width of the concrete block. Tensile stresses appear at the level of the two upper rows of studs; meanwhile maximum compression stresses are located just in front of the bottom flange of the girder. The neutral axis is situated near the mid-width of the web girder. Other experimental results deal with: stress distributions in several parts of the specimen: stud shanks, slab reinforcement, girder cross-sections…; slip measurements between the slab and the upper steel girder flange; fatigue of some details.

In addition, to reach information not accessible to measurement and to obtain a more accurate interpretation of the test results and a better understanding of some specific behaviour, a 3D finite element model based on CASTEM have been developed [3].

3 DESIGN METHOD OF THE JOINT

3.1 General design approach

The basic design principle adopted is to maintain a distribution of internal forces in the joint as equivalent as possible to the internal force distribution identified in the attached beam cross-section close to the joint. Insofar as such a joint is necessarily located on an intermediate support, only hogging bending moment transmitted by the joint has been considered here. In composite bridge, steel girder cross-sections are often in Class 3 so only elastic analysis has been developed in this study.

3.2 Internal forces transmitted to the joint

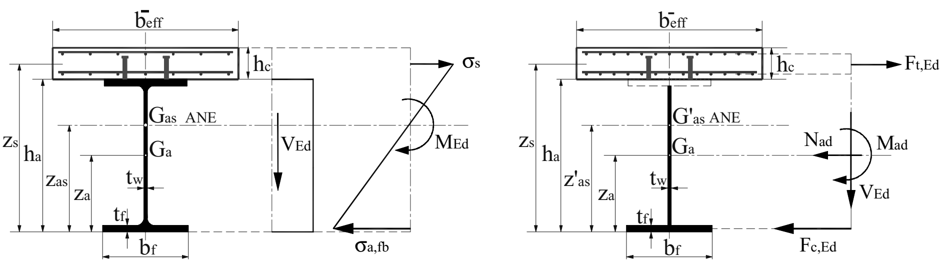


Figure 5: Internal forces transmitted by the composite cross-section to the joint

A shear force V_{Ed} and an hogging bending moment M_{Ed} are transmitted by the attached composite cross-section to the joint. Corresponding stress diagrams are represented in Figure 5. The position of the elastic neutral axis z_{as} of the composite cross-section is determined from the cross-sectional area A_a and the position of the centroid z_a of the steel cross-section and from the cross-sectional area A_s and the position of the centroid z_s of the reinforcement.

To allow the continuity of the composite beam, the joint has to transmit:

- the existing tensile force transmitted by the longitudinal reinforcing bars of the slab;
- the tensile normal force transmitted by the upper flange which is transferred to the longitudinal reinforcing bars (the reinforcement area will be increased and additional shear studs added on the steel beam flange near to the joint to allow the force transfer);
- the compressive normal force transmitted by the bottom flange to the joint;
- the shear force V_{Ed} transmitted by the intermediate zone of the joint located at the web level;

- the remaining equilibrium forces (force and moment) transmitted by this intermediate zone.

The same position z_{as} of neutral axis is adopted so that the stress in the bottom steel flange is unchanged; consequently the tensile stress in the reinforcement is also unchanged if no slip is assumed at the steel-concrete interface. The new longitudinal reinforcement area A'_s is given by:

$$A_s^{'} = \frac{A_a(z_{as} - z_a) + b_f t_f (h_a - t_f / 2 - z_{as})}{z_s - z_{as}} \tag{1}$$

See notations in figure 5 (*the elastic modulus of steel reinforcement is considered equal to the one of structural steel and the area of radius under the upper tension flange of the steel section is neglected*).
So, the tensile normal force $F_t = A^{'}_s\sigma_s$ in the longitudinal reinforcement and the compressive force is $F_c = b_f t_f \sigma_{a,fb}$ in the cross-sectional area of the bottom steel flange; where σ_s and $\sigma_{a,fb}$ are the stresses defined at the centroids of reinforcement and lower flange, respectively are easily determined (figure 5).
Additional internal forces N_{ad} and M_{ad} determined at the centroid G_a of the steel section (figure 5) are introduced to ensure the cross-section equilibrium.

3.3 Design of the additional reinforcement of the slab

The additional reinforcement area $A_{s,ad}$ is chosen immediately equal to or greater than $A^{'}_s - A_s$. The corresponding additional bars are distributed over the effective width b^{-}_{eff} of the composite beam (see 5.4.1.2 of EN 1994-2 [4]) on a length $\ell_{s,ad} = 2(b^{-}_{eff} + \ell_{bd})$ where b^{-}_{eff} is related to the reinforcement on each side of the joint and ℓ_{bd} is the design anchorage length defined in 8.4 of EN 1992-1-1 [5]. According to $A_{s,ad}$ a new value of the position $z^{'}_{as}$ of the neutral axis is calculated (*slightly different from* z_{as}).

3.4 Design of the additional shear connection between the concrete slab and the steel girder

The number of additional shear studs to be distributed on a length approximately equal to b^{-}_{eff} on each side of the joint is given by: $n_{ad} \geq A_{s,ad}\sigma_s / P_{Rd}$ where P_{Rd} is the shear stud resistance given in 6.3.2.1 of EN 1994-1-1 [6]. The transverse steel reinforcement in the slab has to be checked again to take into account the increase of the longitudinal shear force near the joint so that any premature longitudinal shear failure and longitudinal splitting are prevented (EN 1994-2, 6.6.6 referring to EN 1992-1-1, 6.2.4).

4.6 Butt-plate design

The thickness t_p of the butt-plates is preliminary defined in order to assume the transmission of the compression forces $F_{c,Ed}$ from the bottom flanges to the concrete transverse deep beam:

$$F_{c,Ed} \leq f_{jd} b_{eff} \ell_{eff} \text{ ; where } b_{eff} = b_f + 2c \text{ and } \ell_{eff} = t_f + 2c \text{ , with } c \leq t_p \sqrt{\frac{f_{yp}}{3 f_{jd} \gamma_{M_0}}} \text{ ; } \gamma_{M_0} = 1.0 \tag{2}$$

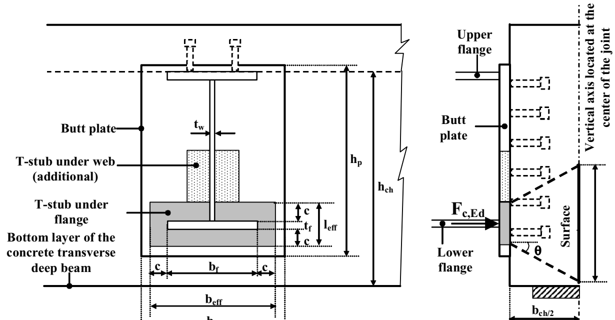


Figure 6: Butt-plate thickness design

b_{eff}, b_f, c, ℓ_{eff} are defined in figure 6. f_{yp} is the yield strength of the butt-plate and f_{jd} is the design bearing strength between the butt-plate and the concrete block. f_{jd} is determined from the design method proposed in EN 1993-1-8, 6.2.5 [7] for column bases loaded by normal force and bending moment. The width of the concrete transverse deep beam b_{ch} should be defined in order to allow a distribution of the compression force on the half-width $b_{ch}/2$ (figure 6) just to permit to put studs of the butt-plates in place keeping a sufficient gap between the opposite heads (a width b_{ch} equals about three times the shank height of the studs of the butt-plates would be sufficient to satisfy these conditions). In addition, the height h_{sc} of the transverse beam should be defined in order to allow the formation of compressive struts in the concrete of the bottom part of the transverse beam:

$$h_{sc} = h_a - \frac{t_f}{2} + \frac{\ell_{eff}}{2} + \frac{b_{ch}}{2} tan\theta \;;\; \text{with } 26{,}5° \le \theta \le 45° \tag{3}$$

The beam ends will be connected to the butt-plates by means of a fillet weld. Welds are designed by taking into account vertical shear V_{Ed} along with the additional forces N_{ad} and M_{ad} [7].

4.7 Butt-plate anchors design

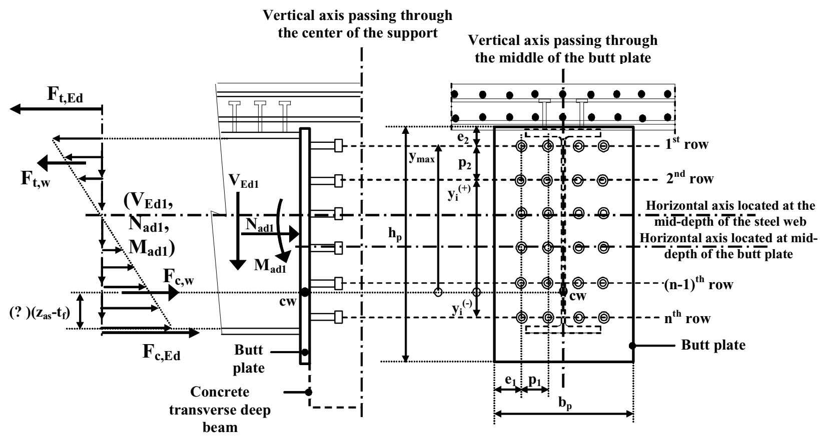


Figure 7: Butt-plate anchors design

Headed studs of the butt-plate should be placed on several rows and lines with respect to the spacing conditions set forth in Clauses 6.6.5.5 to 6.6.5.7 of EN1994-2 [4]. They are designed in order to transmit to the transverse concrete beam the vertical shear load V_{Ed} and the equilibrium forces N_{ad} and M_{ad} .

Calculation of the shear force inside the studs of the butt-plate takes into account the resistance contributed by friction $F_{f,Rd}$, within the compression zone, between the butt-plate and the transverse concrete beam. Moreover a uniform distribution in shear forces can be assumed between the $n_{con,w}$ connectors. The shear force $F(V_{Ed})$ transmitted by each connector is thus expressed as:

$$F(V_{Ed}) = (V_{Ed} - F_{f,Rd}) / n_{con,w} \ge 0 \;; \quad \text{with: } \; F_{f,Rd} = C_{f,d} \left| F_{c,Ed} \right| \tag{4}$$

$C_{f,d}$ is the coefficient of friction between the butt-plate and the transverse concrete beam. A value of $C_{f,d}$ = 0.2 can be assigned, which corresponds to a contact between sand mortar and cement. For purpose of recall, $F_{c,Ed}$ is the compressive force contributed by the compression beam flange.

Following conclusions of ref. [8], specifications of ACI 318-08, appendix D [9], have been adopted to compute the strength of headed stud under tension (CCD method) or combined tension and shear.

The strength of a single stud or group of $n_{con,w}$ studs in tension is based on a two-stage verification:

- as governed by the steel strength : $P^{(1)}_{ten,Rd} = n_{con,w}.\dfrac{\pi d^2}{4}.\dfrac{f_u}{\gamma_v}$ (N); (5)

where d (mm) is the shank stud diameter and f_u (N/mm^2) the ultimate tensile strength not be taken greater than the smaller of $1.9f_y$ and 800 N/mm^2. The recommended value of the partial factor γ_v is 1.25 [6].

- as governed by the concrete breakout strength: $P^{(2)}_{ten,Rd} = 15.5\dfrac{A_{Nc}}{A_{Nco}}(h_{sc} - k)^{1.5}\dfrac{\sqrt{f_{ck}}}{\gamma_v}$ (N); (6)

where h_{sc} is the depth embedment and k the height of the stud head. A_{Nc} is the projected concrete failure area of a single stud or group of studs that shall be approximated as the base of the rectilinear figure that results from projecting the failure surface outward $1.5(h_{sc} - k)$ from the centrelines of the stud, or in the case of a group of anchors, from a line through a row of adjacent studs (figure 8). A_{Nc} shall not exceed $n_{con,w,gr}\ A_{Nco}$ where $n_{con,w,gr}$ is the number of tensioned studs in the group. $A_{Nco} = 9(h_{sc} - k)^2$ is the projected concrete failure area of a single stud (Fig. 9) with an edge distance equal to or greater than $1.5(h_{sc}\text{-}k)$. Modification factors may be introduced in (13), (14) and (15) to take account of tension load eccentricity, edge effects and cracked or uncracked concrete [9].

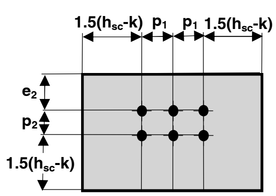


Figure 8: Projected area A_{Nc} for a group of studs

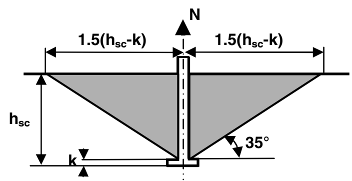


Figure 9: Section through failure cone (A_{Nco})

The general requirement for the strength design of butt-plate studs, including the interaction when studs or group of stud are subjected to both shear and axial loads may be given by the following general shear and tensile load interaction equation suggested with the reference [9]:

$$\left[\left(\frac{F(N_{ad}) + F(M_{ad})^{max}}{P^*_{ten,Rd}}\right)^{\frac{5}{3}} + \left(\frac{V_{Ed} - F_{f,Rd}}{n_{con,w}P^*_{Rd}}\right)^{\frac{5}{3}}\right] \leq 1{,}0 \qquad (7)$$

where $F(N_{ad})$ and $F(M_{ad})^{max}$ are the normal forces due to N_{ad} and M_{ad} for the highest row of studs. $P^*_{ten,Rd}$ and P^*_{Rd} are the lowest strengths determined from appropriate failure modes. In order to take into account the potential risk of failure to a concrete block around studs, the strength of each group of connectors will be checked successively beginning with the highest row, followed by the group of two highest rows and so forth until the strength derived is greater than the previous value.

4.6 Design of the concrete transverse beam reinforcement

4.6.1 Stud reinforcement for shear

Transverse reinforcing bars placed close to the studs of the butt-plate have to transmit the resultant shear force ($V_{Ed} - F_{f,Rd}$) through a shear failure surface defined in a manner similar to that adopted to define the longitudinal shear strength of concrete flange (EN 1994-1-1, 6.6.6). The required total area of this transverse reinforcement is so determined.

4.6.2 Supporting reinforcement

Supporting reinforcement serves to raise the previous resultant shear force ($V_{Ed} - F_{f,Rd}$) towards the upper part of the section; consequently a total area $A_{s,s}$ of the transverse reinforcing is determined.

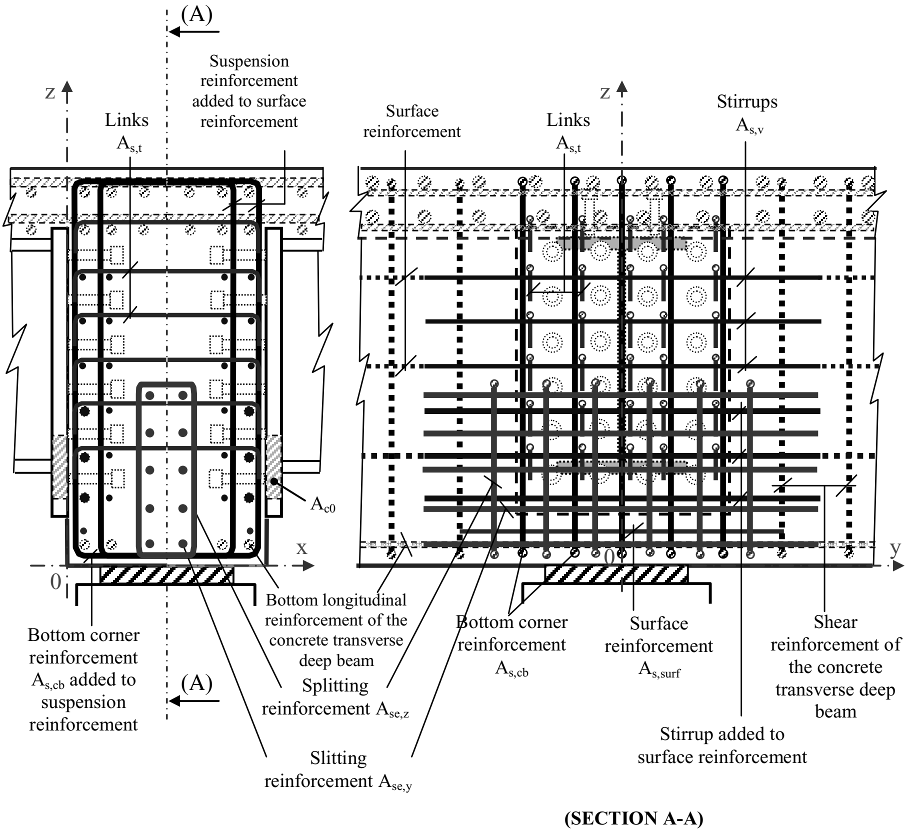


Figure 10: Reinforcement of the concrete block

4.6.3 Links (stud reinforcement for tension)

Links are introduced to improve the bonding of the both connected sides B1 and B2 through the concrete transverse beam thickness. The area of the links is defined on the basis of the maximum tensile force to be transmitted by the first stud row located in the upper part of the butt-plate.

4.6.4 Reinforcement in the compression zone of the concrete transverse beam

The compressive force transmitted by the bottom flange of the steel girder exerts a local effect of pressure onto a reduced contact surface area A_{c0} of the side surface of the concrete transverse beam. A reinforcement may be designed, which comprise both surface reinforcement $A_{s,suf}$ and splitting reinforcement $A_{se,y}$ and $A_{se,z}$ in both directions y and z, positioned beginning at a depth of 0.2 until reaching 0.8 of the half width $b_{ch}/2$ of the concrete transverse beam and distributed over lengths equal to $\ell_{\mathrm{eff}} + b_{ch}\tan\theta$, in vertical z direction vertical, and $b_{eff} + b_{ch}\tan\theta + 2\ell_{bd}$, in horizontal y direction (figure 6).

4.6.5 Reinforcement at the bottom corners

In order to prevent premature splitting or spalling of concrete of corners when exposed to the simultaneous action of compressive forces applied by the lower part of the butt-plates and the support reaction, it must be checked that the various reinforcements crossing the splitting failure plane are adequate in all directions of the plane (figure 6).

4.6.6 Example

Figure 10 shows the example of the reinforcement design adopted for the joint specimen tested at INSA Rennes Laboratory. Main characteristics of the specimen have been given in the previous § 2.

4.7 Fatigue resistance verification of the joint

According to Eurocode requirements, the fatigue resistance of various details as: longitudinal reinforcement, headed studs, welds, compressed concrete, and bottom flanges should be checked.

5 CONCLUSION

This paper provides useful guidance elements for the design of beam-to-beam butt-plate joints stud-connected to concrete transverse beams in composite bridges. Experimental and numerical results of researches conducted at the INSA-Rennes like Eurocode-based methods have been assigned priority for the design methods developed herein. Other standards were also applied whenever the topic examined was not covered by Eurocodes.

ACKNOWLEDGEMENTS

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