Application of High Strength Steel Dowels in Steel –To- Timber Double Shear Joints with A Central Steel Plate

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Abstract

Combination of insufficient data and legislations and non-adapted design codes has negative influence on the application of HS(high strength) steel in structures even when economic advantages are evident. The use of high strength steel may give economical advantages in terms of less material use or new applications. The use of HSS also offers the opportunity to optimize timber joints.

The problem of steel to timber connection is faced in various structural codes such as EC5 (EN1995-1-1) [1] by using verification formulas. A point of major concern, regarding the implementation of HSS dowels in timber connections is that the existing design rules are based on test data of connections with mild steel dowels and soft woods. Hence the use of HSS fasteners raises questions which are related to different properties of the HSS compared with mild steel.

The main aim of this research was to evaluate how the higher strength and the less ductility of the HSS dowels influence the load-carrying capacity and the deformation capacity at maximum load of timber connections, compared this to connections with mild steel dowels.

To address the objectives of this study an experimental program, testing double shear steel to timer connections with HSS or mild steel dowels and tropical hard woods, was carried out. In these tests following main parameters varied:

-the timber specie (hard woods Cumaru and Azobe)

-the quality of the steel dowels (mild steel S235 and HSS 12.9)

-the number of dowels in the row (one, three and five dowels in a row)

Twelve test specimens were designed. For each test specimen 5 tests have been tested. In total 60 timber connections will be tested. Besides these tests, mild steel and HSS dowels were tested in order to define the yielding stress of steel dowels.

The test results showed that the connections with HSS dowels, same number of dowels and the same timber species, have higher load-carrying capacity than connections with mild steel dowels. These differences in strength decrease for multiple dowels connections compared to one dowel connections because for connections with multiple mild steel dowels the test effective numbers are higher.

The effective numbers, calculated from test results, are different from effective numbers calculated from EC5 formula. Modifying the EC5 formula by introducing a coefficient β, which take in consideration the combined effects of material properties, yield stress of dowels and on embedment strength of timber, improves significantly the effective number calculations.

The HSS can be used in steel to timber connections. They have enough plasticity to develop full plastic hinges.

Comparing the tests results with EC5 predictions can be concluded that the predicted load-carrying capacity of one dowel connections coincides well with measured values from the tests. The predicted failure modes according to EC 5 occurred almost for all the connections. Observing the test specimens can be concluded that the main failure modes can accurately describe by the Johansen models and the plastic hinges could develop without splitting of the timber.

KEYWORDS: timber connections, high strength steel dowels, mild steel dowels, failure modes, plastic hinges, effective number.

1. INTRODUCTION

The research presented in this report will be focused only in double shear steel to timber connections with mild steel or HSS dowels and tropical hardwoods. The EC5 (EN1995-1-1) [1] formulas predict the load carrying capacity of the steel to timber connections with single dowel based on Johansen's yield model and on the concept of effective number. This model predicts three discrete failure modes.

The strength of the multiple dowels connection is not equals the strength of the single dowel connection multiplied by the number of dowels. The multiple dowels connection fails at a lower load because the timber splits and /or because of softening of the wood, which can be explained by the complicated stress distribution around dowel position (only when force vector and wood fibers are in the same direction). The effective number takes in consideration these effects. Based on codes, as EC5 (EN1995-1-1), the three main parameters that effect the effective number are a (spacing between holes), d (diameter of dowels) and n (number of dowels in a row). Hence do the strength parameters (embedment strength of the timber and yield strength of the steel) influence the effective numbers of fasteners? For the purpose of this research an experimental method is defined and the program is executed step by step.

2. THE STRENGTH OF A STEEL-TO-TIMBER JOINT FROM EC5 [1]

In the figure 2.1 and 2.2 are shown the formulas and the schematic representations of the three failure modes based on EC5 design rules for steel to timber connections. The minimum value of these three formulas calculates the load carrying capacity of the connection per single shear and one dowel.

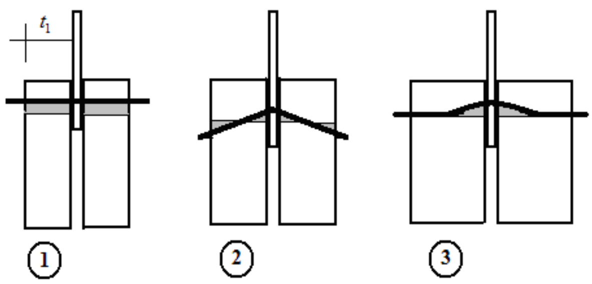

Figure 2.1 The schematic representations of failure modes for the steel-to-timber double shear joint [1]

$$\mathbf{F_{v,R}} = \min \begin{cases} (1)\, f_{h,1} t_1 d \\ (2)\, f_{h,1} t_1 d \left[\sqrt{2 + \dfrac{4M_{y,R}}{f_{h,1} d t_1^{\,2}}} - 1 \right] \\ (3)\, 2\sqrt{M_{y,R} f_{h,1} d} \end{cases}$$

Figure 2.2 The formulas of failure modes for the steel-to-timber double shear joint [1]

$F_{v,Rk}$, $f_{h,1k}$, t_1, d, $M_{y,Rk}$ -the characteristic load-carrying capacity per shear plane per fastener, the characteristic embedding strength in timber member, the thickness of timber side member, the diameter of the fastener, the characteristic fastener yield moment.

For the determination of the yield moment for HSS and mild steel dowels will be used the equation [2.1] of full plastic moment.

$$M_{y,mean} = f_{y,mean} \frac{d_{nom}^3}{6} \quad [2.1]$$

$f_{y,mean}$ d -the mean yield stress from tensile tests, the diameter of the dowel

For one row of dowels parallel to the grain direction with two shear plane per dowel the effective characteristic load-carrying capacity parallel to the grain should be taken as.

$$F_{v,ef,Rk} = 2\eta_{ef} F_{v,Rk} \quad [2.2]$$

In EC5 the influence of the number of dowels in a row is taken into account by:

$$n_{ef} = \min \begin{cases} n \\ n^{0.9} \sqrt[4]{\dfrac{a_1}{13d}} \end{cases} \quad [2.3]$$

n_{ef}, a_1, n -the effective number, the dowel spacing, the number of the fasteners in a row

This equation indicates no dependency of effective number on either the dowel yield strength or on the embedment strength of timber (or combination) where this may be expected. It means that a joint with HSS is equally treated as a joint with low strength steel.

3. TESTS ON DOUBLE SHEAR STEEL TO TIMBER CONNECTIONS

3.1. Tests design

The experimental program of this study consists of 12 test specimen (five tests for each test specimen-60 tests in total) for one dowel connections, three dowels connections and five dowels connections with mild steel or HSS dowels and tropical hardwoods Azobe or Cumaru.

Each test specimen (figure 3.1) has two connections. The performance of the test specimen is analyzed for one of the connections. The other connection is designed with higher load carrying capacity and acts as a supporting part.

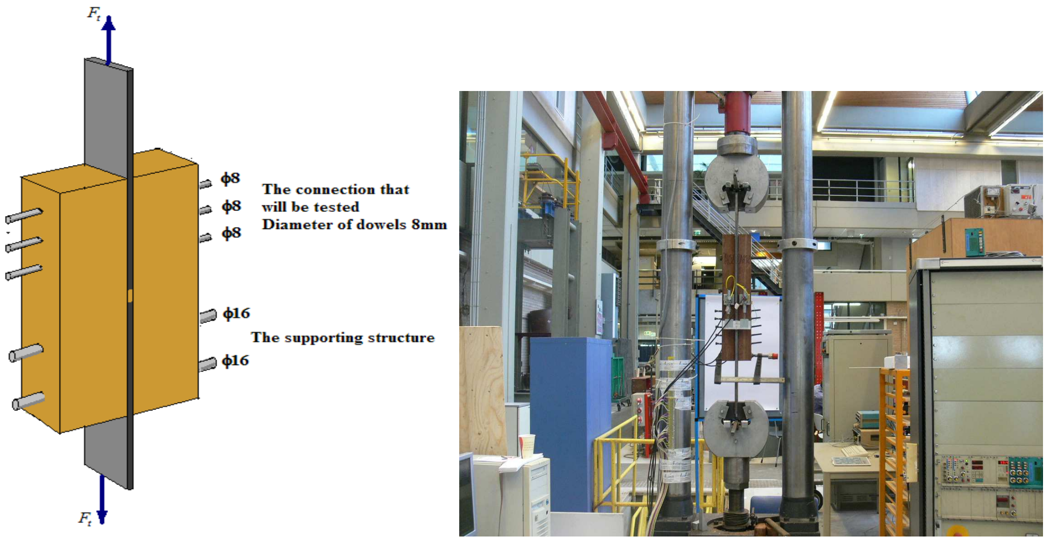

Figure 3.1 The test specimen and the testing machine with the test specimen mounted on it

For the timber specimens will be used two species of tropical hardwoods Cumaru and Azobe. In order to define the thickness of timber specimens the prediction from formulas of EC5 [1] will be used.

Based on this predictions, for HSS 12.9 dowels and Azobe and Cumaru hardwoods with average density about 1035kg/m3 (from the measured densities) the connection fails in failure mode 2 for t1=50mm and in failure mode 3 for t1=60mm. For the Cumaru was chosen e thickness t1=55mm (based on the prediction this thickness is a boundary between second and third failure mode). For the Azobe was chosen a thickness t1=65mm (based on the prediction for this thickness result a third failure mode). The second and the third failure mode are of interest because they are associated with the formation of plastic hinges in dowels.

For minimal values for spacing, edge and end distance for dowels in timber connections the conditions from EC5 will be used. For the design of the tests the angle between the load and grain direction is assumed $a = 0^\circ$. The diameter of the dowels is 8mm. For this angle the conditions for minimum values are:

The spacing between dowels $a_1 \geq 5d$ =40mm, the loaded end distance $a_{3,t} \geq \max(7\,d, 80\,\text{mm})$, the unloaded end distance $a_{3,c} \geq 4d$ =32mm, the loaded edge distance $a_{4,t} \geq 3d$ =24mm, the unloaded edge distance $a_{4,c} \geq 3d$ =24mm.

The dowels that will be used are $\phi 8$ mm HSS 12.9 and mild steel S235 for the connection and dowels $\phi 16$ mm HSS 8.8 for the supporting connection.

The material of steel plates is steel S690. For the test specimen are necessary two central steel plates (one set). One steel plate is part of the connection which will be tested and the other steel plate is part of the supporting connection. Both ends of the steel plates after the test specimen is assembled will be clamped into the arms of testing machine. The moisture content of Azobe timber was from 20-30% and for Cumaru timber was from 12-18%.

3.2. Tests execution based on the international standard EN 26891:1991(E) [2]

A testing machine figure 3.1 able to apply and record load with an accuracy of $\pm 1\%$ of F_{est}

Four LVDT to measure the slip deformation of the connections under the load with an accuracy of $\pm 0.02mm$

The maximum load reached before or the force at a slip 15mm shall be rerecorded as the maximum load $F_{\max}$ for each specimen.

3.3. Materials

For the determination of the dowels yield stress, two groups (one group for mild steel dowels and the other group for HSS dowels) of tensile tests were performed, each one with two specimens. For the determination of yield stress from each test the 0.2% yield limit is used, which is the stress where a strain of 0.2% remains after unloading. For unloading at 0.2% remaining strain is assumed a Young modulus of Es=200000 N/mm2 which is available from literature. Average value of the yield stress for HSS dowels is (1252+1240)/2=1246 N/mm2. Hence the yield stress of the HSS dowels is about 15% more than the charac teristic one (1080 N/mm2). Average value of the yield stress for mild steel dowels is (544+527)/2=535 N/mm2. The embedment strength of the timber material will be calculated from its relation with the density from the formula $f_h = 0.102(1-0.01\mathrm{d})\rho$ [1], [10] taking in consideration the influence of the moisture content.

4. TEST RESULTS AND OBSERVATIONS

Twelve different test specimens were designed, 5 tests were performed for each one of them (in total 60 tests). Table 4.1 lists the maximum loads, the slip deformation at maximum load and the failure mechanism for each test specimen. From the results three tests are excluded because of wrong settings in test set-up. The values of the maximum forces are averages for the tests made for each type of test specimen. The maximum forces of these tests (five or four) didn’t have major deviations between each other. The coefficients of variation of the maximum forces are less than 8%. This way the averages of the maximum forces are accepted as representative of the tests for each type of test specimen and will be used for further analyses. Observing the load slip curves for each test the embedment failure and splitting failure can be define. When, after the maximum force is reached, the connection continues to slip without decreasing the force (the force remain almost constant until the splitting occurs as result of continuation of the test) then the embedment failure occurs. When, after the maximum force is reached, the connection continues to slip by decreasing the force significantly then the splitting failure occurs. The values of densities presented in table 4.1 are average values per joint. In table 4.1 the maximum slip deformations Vmax of the tests for each type of test specimen have significant differences. This way the average of the slip deformation is not representative for the test specimens.

Table 4.1-Test result for each test specimen

Test specimen ID	**Density**	**Average Fmax**	**CoV Fmax**	**Vmax (mm)** the slip deformation where the largest load is registered (green: **Clamped joints**; blue: **Unclamped joints**)					**Number of tests** **Failure Mode of connection and type of timber failure (S-Splitting) (E-Embedment)**				
	Kg/m3	**[KN]**	**%**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
JAM 1	(1045)	28.1	6.2	17.04	17.68	17.14	11.5	10.49	3/S	3/E	3/E	3/E	3/S
JAH 1	(1154)	46.5	5.8	19.02	15.92	12.29	14.67	17.95	3/S	3/S	3/S	3/S	3/S
JCM 1	(922)	28.5	1.5	19.54	10.52	7.8	8.8	11.27	3/S	3/S	3/S	3/S	3/S
JCH 1	(1009)	44.3	7.2	9.25	13.58		15.86	12.85	2/S	3/S		3/S	3/S
JAM 3	(1061)	71.5	5.7	7.05	6.04	5.2	6.18	3.95	3/E	3/E	3/E	3/E	3/S
JAH 3	(1138)	96.6	1.1	5.2		6.2	6.8	6.5	3/S		3/S	3/S	3/S
JCM 3	(901)	70.2	2.3	3.99	5.26	4.82	6	13.73	3/E	3/S	3/E	3/E	3/E
JCH 3	(947)	94.2	4.3	5.14	6.54	3.52	6.39	5.46	3/S	2/E	2/S	2/S	2/S
JAM 5	(1058)	107.5	5.1	5.41	7.68	4.89	4.97	3.49	3/S	3/S	3/S	3/S	3/S
JAH 5	(1119)	146.2	6.5	5.41	7.68	4.89	4.97	3.49	2/S	2/S	2/S	2/S	2/S
JCM	(878)	104.5	7.7	2.8	3.0	3.0	4.0	3.2	3/S	3/S	3/S	3/	3/

5				1	2	5	1	4				S	E
JCH 5	(1089)	141.8	6.4	3.0 4		3.9 7	2.3	2.6 5	2/S		2/S	2/ S	2/ S

Test specimen ID: First letter J-joint, Second letter A-Azobe,C- Cummaru, Third letter M-Mild Steel, H-HS Steel, Fourth letter 1,3,5-Number of Dowels.

5. THE EFFECTIVE NUMBER

In table 5.1 the tests effective numbers (ratio of average maximum forces between connection with the same dowel material, the same timber species and different number of dowels in a row) and the theoretical effective numbers form EC5 formula have been listed.

Table 51-The effective numbers

Number of dowels in a row	Ratio of average Fmax (Tests effective numbers)		EC5 effective numbers n_{eff}
3	(JAM3)/ (JAM1)	2.54	2.12
5	(JAM5)/ (JAM1)	3.82	3.35
3	(JCM3)/ (JCM1)	2.55	2.12
5	(JCM5)/ (JCM1)	3.80	3.35
3	(JAH3)/ (JAH1)	2.08	2.12
5	(JAH5)/ (JAH1)	3.14	3.35
3	(JCH3)/ (JCH1)	2.13	2.12
5	(JCH5)/ (JCH1)	3.21	3.35

Using HSS dowels has as consequence the introduction of higher loads in timber specimens which results in a more severe stress distribution (stress around dowels) before the maximum load is reached. The stress distribution and strength material properties of timber define the softening or cracking of the timber specimen, which are two phenomena that influence the effective number. Hence a possible influence in the effective number of the material properties of dowels and timber is expected. For connections with HSS dowels lower effective numbers are expected then connections with mild steel dowels because more brittle failures are expected. The strength parameters that will be focused are the embedment strength of the timber and the yielding stress of steel. From the table 5.1 it can be concluded that for connections with HSS dowels there is a decrease in effective numbers of fasteners, from 2.12(EC5) to about 2.08 (test result) and from 3.35 (EC5) to about 3.14 (test results) respectively for three and five dowels connections. For connections with MS dowels the tests effective numbers are higher than the effective numbers of fasteners with HSS dowels.There is a small difference between Azobe and Cumaru timber.

The EC5 equation indicates no dependency of the effective number on the material properties of dowels or/and timber material. The results indicated above show that there is an influence of the yield strength and the timber material properties in the effective number. To evaluate the synergic effects of material properties of dowels and timber in the effective number a parameter

β called the material coefficient is introduced.

$$\beta = \frac{E_s E_{0,mean}}{f_y f_{h,mean}} \quad [5.1]$$

β, E_s, $E_{0,mean}$, f_y, $f_{h,mean}$ - the material coefficient, the elastic modulus of the dowels material from literature 200000 N/mm2, the mean elastic modulus of the timber material parallel to the grain for the highest grade of hardwoods in dry conditions, D70, 20000N/mm2 [3], the mean yield stress of the dowels material form tensile tests (535 N/mm2 for mild steel and 1246 N/mm2 for HSS dowels), the mean embedment strength of the timber (used for the tests specimens) calculated from density (102 N/mm2 for Azobe and 90 N/mm2 for cumaru).

The trend lines(from linear regressions) of the relation β- test effective numbers presented in (figure 5.1) for three and five dowels connections are further modified.

For three dowels connections:

$$Test(n_{eff}) = 0.5955\beta^{0.213} = 2.12*0.28\beta^{0.213} = 3^{0.9}\sqrt[4]{\frac{40}{13*8}}*0.28\beta^{0.213} = n^{0.9}\sqrt[4]{\frac{a_1}{13d}}*0.28\beta^{0.213} = EC5(n_{eff})*0.28\beta^{0.213}$$

[4.3]

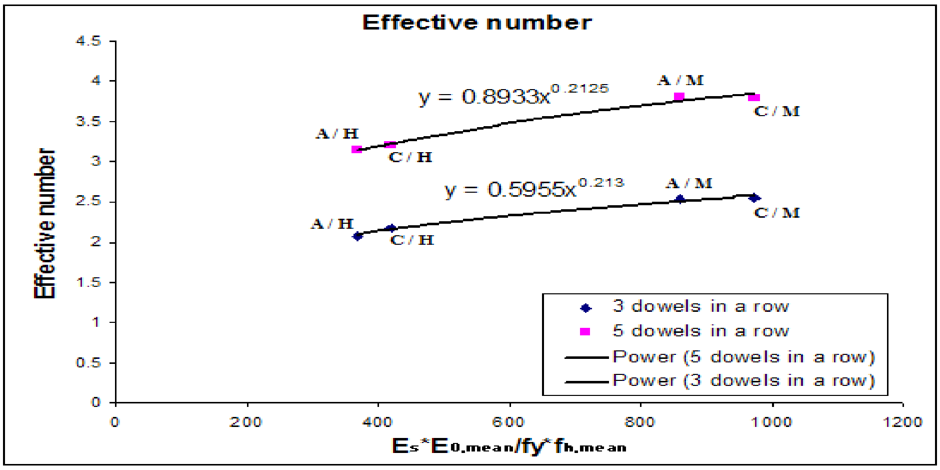

Figure 5.1- The influence of material coefficient β on effective number

For five dowels connections:

$$Test(n_{eff}) = 0.8933\beta^{0.2125} = 3.35*0.27\beta^{0.2125} = 5^{0.9}\sqrt[4]{\frac{40}{13*8}}*0.27\beta^{0.2125} = n^{0.9}\sqrt[4]{\frac{a_1}{13d}}*0.27\beta^{0.2125} = EC5(n_{eff})*0.27\beta^{0.2125}$$

[4.4]

The mean value of the percentile difference between the tests effective number and the effective numbers determined by equation [4.3] and [4.4] is $\mu = 1.66\%$ and

$\mu = 2.9\%$. The standard deviation of this difference is $\sigma = 0.032$ and $\sigma = 0.037$. In the formulas [4.3] and [4.4], except the parameter β also the parameters given in EC5 are present. The formulas [4.3] and [4.4] present an idea to how the EC5 formulas of effective number can be modified.

6. COMPARISON OF TEST VALUES WITH BASIC JAHANSON FORMULAS

The Johanson formulas describe equilibrium equations. When the real parameters can be calculated, the use of Johanson formulas for comparison is a straightforward approach. Table 6.1 lists for each test configuration the average maximum test load Fmax and the average predicted resistance from Johanson formulas Fp,R. For these calculation are used the embedment strength of the timber measured form the density (12 % moisture content of the timber elements used for the connections) and the mean yield stress of the dowels calculated for the tensile tests.

Table 6.1 -Maximum load from test results and EC5 predictions

Test Specimen	**Test Fmax [KN]**	**Johanson $F_{p,R}$ [KN]**	**Error (F_{max}-$F_{p,R}$)/$F_{p,R}$ %**
JAM1	28.1	24.2	16.3
JAH1	46.5	38.0	22.3
JCM1	27.5	22.8	20.8
JCH1	41.7	36.1	15.8
JAM3	71.5	51.1	39.9
JAH3	96.6	79.8	21.0
JCM3	70.2	47.5	47.8
JCH3	94.2	74.2	27.0
JAM5	107.5	80.4	33.7
JAH5	146.2	127.2	14.9
JCM5	104.5	75.0	39.3
JCH5	139.3	118.1	17.9

Observing the table 6.1, it can be concluded that:

The test values are always above the values predicted from Johanson formulas. For single dowel connections there are no significant differences between connections with mild steel dowels and connections with HSS dowels. For multiple dowel connections there are significant differences between connections with mild steel dowels and connections with HSS dowels. This is related with the differences between test effective numbers and effective numbers calculated from formula EC5 [2.3].

7. CONCLUSIONS

A series of tests were carried out on double shear steel to timber connections with mild steel or HSS dowels and tropical hardwoods slotted in steel plate.

The test results showed that the load carrying capacity of the connections with one HSS is 55-65% higher than the carrying capacity of the connections with one mild steel dowel. The load carrying capacity of the connections with three or five HSS dowels is 34-36% higher than the carrying capacity of the connections with three or five mild steel dowels.

For connections with multiple mild steel dowels the test effective numbers are higher than for connections with multiple HSS dowels. Modifying the EC5 formula by introducing a coefficient β, which take in consideration the combined effects of material properties of timber and dowels, improves significantly the accuracy of the effective number calculations.

The test data indicate that HSS dowels used for the tests have the necessary rotational capacity to developed full plastic hinges.

Introducing Azobe instead of Cumaru, with the same number of dowels and the same dowel type, increases the strength of the connections (higher density).

For multiple dowel connections there are significant differences between connections with mild steel dowels and connections with HSS dowels. The theory of Johansen (presuming moisture content 12%) is applicable and safe but must be associated with the appropriate calculation of the effective numbers. The predicted failure modes according to Johanson occurred almost for all the connections.

All the empirical formulas and conclusions are based on limited test data and hold only within the boundary of this study. For more accurate conclusions further investigations are necessary.

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