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DESIGN OF CONNECTIONS IN COMPOSITE TIMBER-CONCRETE STRUCTURES

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Abstract. *This work deals with composite timber concrete structures. By combining timber and concrete in new type of composite material and using the best properties both materials, the high tensile strength of a timber and the high compressive strength of a concrete, depending of different building conditions we can find a lot o reasons for decision to apply this type of the structure in comparison to concrete or steel structure. Here, design methods and procedures for determination of load bearing capacity bar-shaped connectors (fasteners) very often used as element connecting timber and concrete in composite structures will be given. The procedure will be exposed and explained according to the new fashioned methods collected as set of Euro-norms in Eurocode 5. The design equations in Eurocode 5 derived from Johansen's work are based on a rigid plastic behavior of the fastener under bending moments and the timber under embedding stresses and take into account the plastic moment capacity of the fastener.*

Key words: *composite timber concrete structures, load bearing capacity bar-shaped connectors Johansen's theory, Eurocode 5.*

1. INTRODUCTION

The design of the composite joint in composite structures is the crucial point. The connecting system (connector) has to be able to transfer the shear forces and in addition the stiffness of the system is the characteristic value of the elasticity of the compound and from that it determines the bending stiffness of the beam. Investigations with regard to the design of structure details and consisting elements of timber-concrete composite structures and connections are performed especially in Swiss, Italy and Scandinavia. Tests were realized with a different types of connecting systems as:

- bar-shaped connectors (nails, screws, dowels, reinforcing bars),
- special steel components (nail plates, headed studs, shear connectors, beam supports),
- concrete cams with dowels or nails.

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This part of work deals with design methods and procedures for determination of load bearing capacity bar-shaped connectors (fasteners), very often used as element connecting timber and concrete in composite structures. Here will be given needed equations and rules for calculation load bearing capacity of dowel and bolts used for coupling of a main composite footbridge girder and connecting main and secondary girders of a structure.

The procedure will be exposed and explained according to the new-fashioned methods collected as set of Euro-norms in Eurocode 5.

Therefore, the load bearing capacity of connections with dowel type fasteners like bolts, dowels and nails determined according to Johansen theory, depends on the geometry of connection, the bending resistance of the dowel and the embedding strength of the timber.

For the bending resistance of the dowel Johansen assumed the elastic moment capacity of the dowel's cross-section.

2. Design according to EC5

The design equations in Eurocode 5, derived from Johansen's work are based on a rigid plastic behaviour of the dowel under bending moments and the timber under embedding stresses and take into account the plastic moment capacity of the dowel.

Three different possible failure modes are possible for timber-timber connections in double shear (figure 1.)

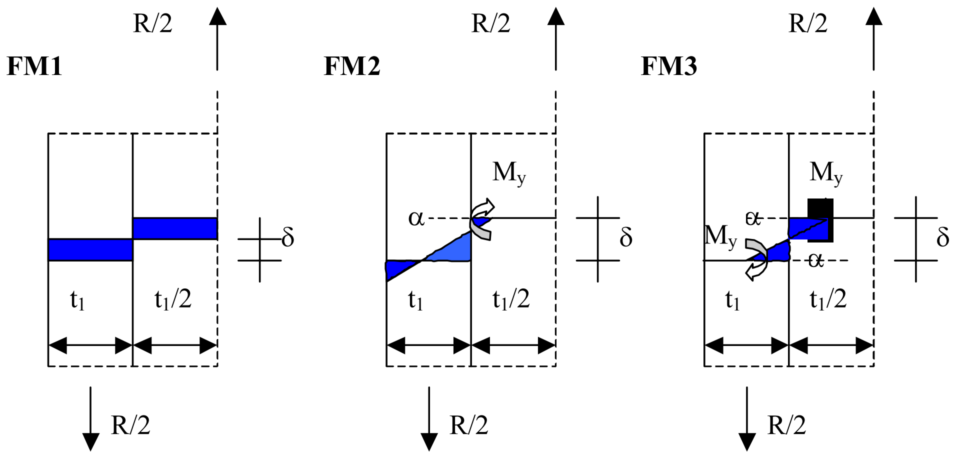

Fig. 1. Failure modes (FM) for timber-timber connections in double shear

Failure mode 1 (FM 1) corresponds to the embedding failure of the middle or side member, respectively. In failure modes 2 and 3, apart from the embedding strength of the wood, the bending capacity of the fastener is reached. Failure modes 2 and 3 of dowels loaded in double shear correspond to identical failure modes of dowels loaded in single shear.

According to EN 409 the yield moment of a fasteners is determined at a bending angle of 45^O. for such a large bending angle, the whole cross-section of the fastener is assumed to be under plastic strain. For bending angles below 45^0 only the outer areas of the cross-section of a fastener are deformed plastically.

For the load-bearing capacity of a fasteners is determined according to EN 26891, the connection strength is defined as the maximum load before a deformation of δ=*15mm* parallel to the load direction reached. The large number of connections tested show that in most cases failure modes 2 and 3 occurred and the bending angles were significantly below $\alpha=45^0$.

It means that the plastic moment capacity of the dowel was not attained in the connection, namely, dowel's cross-section were only partially plasticised. Further, it means lower bending capacity and consequently, lower connection strength values. Therefore, if a deformation limit of *15mm* is assumed for connection the effective bending capacity depends on the yield strength of the fastener material, the fastener diameter and the shape of the moment-angle diagram of the fastener shown on the figure 2.

Moment-angle-diagram evaluated on the base bending test different fasteners. Since the shape of $M(\alpha)$ is very similar for different fastener diameters d, mean curve $M(\alpha)$ was determined and approximated by an exponential function of α expressed by equations:

$$M(\alpha) = (0{,}866 + 0{,}00295\alpha) \cdot \left(1 - e^{\left(\frac{-0{,}248\alpha}{0{,}866}\right)}\right) \tag{1}$$

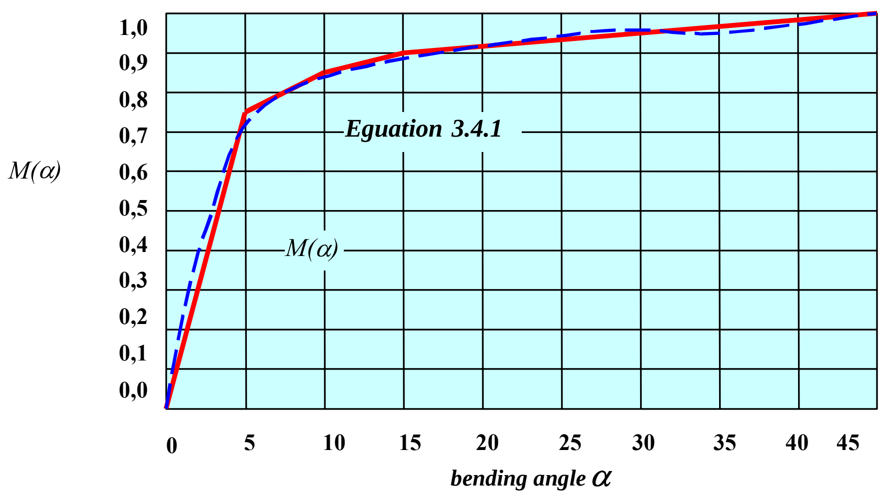

Fig. 2. Mean normalised moment-angle-diagram of dowel–type fasteners and approximation

Further, for the failure modes 2 and 3, maximum deformation δ =*15mm*, length l which corresponds to the length of the wood where the embedding strength is reached, geometry of connection with fastener in single or double shear and take into account that length l depends on the fastener diameter, the embedding strength f_h and the yield moment M_y we can write fallowing relations on the base behaviour of fastener under loading shown on the figure 2.

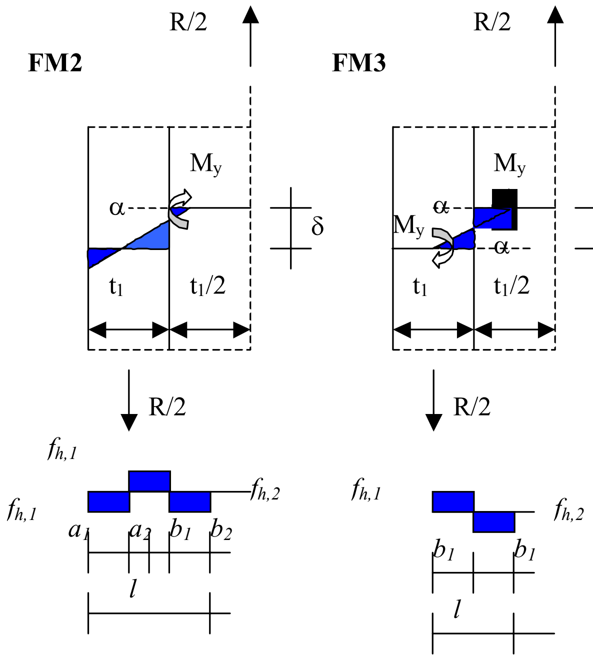

Fig. 3. The bases for derivation equations of load bearing capacity of fasteners, up-figure, down-diagram.

$$\alpha = \arctan\left(\frac{\delta}{\ell}\right) \tag{2}$$

where:

$$\ell = t_1 + b_2 \qquad \text{for failure mode 2} \tag{3a}$$

$$\ell = b_1 + b_2 \qquad \text{for failure mode 3} \tag{3b}$$

For further derivations, we have to have in mind that the fastener yield moment, M_y itself depends on the fastener diameter d and the yield strength f_y of the fastener material and that the embedding strength also is a function of d and of the density ρ.

The derivation of α as a function of the fastener diameter d is shown as an example for failure mode 3 (FM 3). For loading in the direction of a grain and the same density ρ over the cross sections of the members, the embedding strength f_h is constant and consequently, we can write that $b_1 = b_2 = b = l/2$ and from the equilibrium of forces we can determine dimension b and after that the angle α :

$$b = \sqrt{\frac{2M_y}{f_h d}} \tag{4}$$

$$\alpha = \arctan\left(\frac{\delta}{2\cdot\sqrt{\dfrac{2M_y}{f_h d}}}\right) \tag{5}$$

By means of next equation, dependence between the bending moment M_y and bending angle α may be taken into account by an iterative procedure. $\alpha=45^0$ is taken as a first value, in the next step normalised moment according to equation 3.4.1 is calculated and inserted in the same equation and, after three iteration steps the difference $\Delta\alpha$ is less than 1^0.

$$\alpha_{i+1} = \arctan\left(\frac{\delta}{2\cdot\sqrt{\dfrac{2M_{y,k}\cdot M(\alpha)}{f_{h,k}d}}}\right) \tag{6}$$

The parameters influencing $\alpha(d)$ depend on the fastener material and the embedding strength. For bolts, nails and dowels in predrilled holes the embedding strength is determined according to EN 383 as:

$$f_{h.k} = 0{,}082(1-0{,}01d)\rho_k \tag{7}$$

The yield strength in bending f_y according to Eurocode 5 is 80% of the tensile strength $f_{u,k}$ of the steel grade used.

The equation for the yield moment for bolts and dowels given in Eurocode 5 too, has shape:

$$M_{y,k} = 0{,}8 f_{u,k}\frac{d^3}{6} \tag{8}$$

The yields moment of nails with circular cross section with a minimum wire tensile strength of 600N/mm^2 according to Eurocode 5 is:

$$M_{y,k} = 180 f_{u,k} d^{2,6} \tag{9}$$

For the different types of fastener the function α(d) can be determined resulting in minimum values of the bending angle α with governing parameters which are conservatively chosen and resulting as maximum values for the steel tensile strength and minimum values for the characteristic density.

For connections with bolts or dowels, the tensile strength $f_{y,k}$ is chosen as 1000 N/mm^2 and the characteristic density ρ_k as 350 kg/m^3

Inserting these values in equation 3.4.1 results in a relation between the normalised moment and the fastener diameter *d*.

Multiplying $M(\alpha(d))$ and the yield moment according to equation 3.4.7, we can get expression for the effective bending capacity of bolts and dowels for a deformation δ =15mm as fallows:

$$M_{y,k} = 0{,}27 f_{u,k} d^{2,6} \tag{10}$$

where: $f_{u,k}$ fastener tensile strength in N/mm^2,
d fastener diameter in mm.

Equation 3.4.9 for the bending capacity of bolts or dowels takes into account the decreasing bending angle with increasing fastener diameter.

The fallowing part of this chapter consists from chosen rules for determination load bearing capacity of fasteners, firstly, ***load-bearing capacity of dowels and bolts***. Here, will be given rules for embedding of fasteners and distances between them too. The content deals, mainly, with needed elements for calculations connections appearing in the structure of footbridge which will be calculated at the end of work.

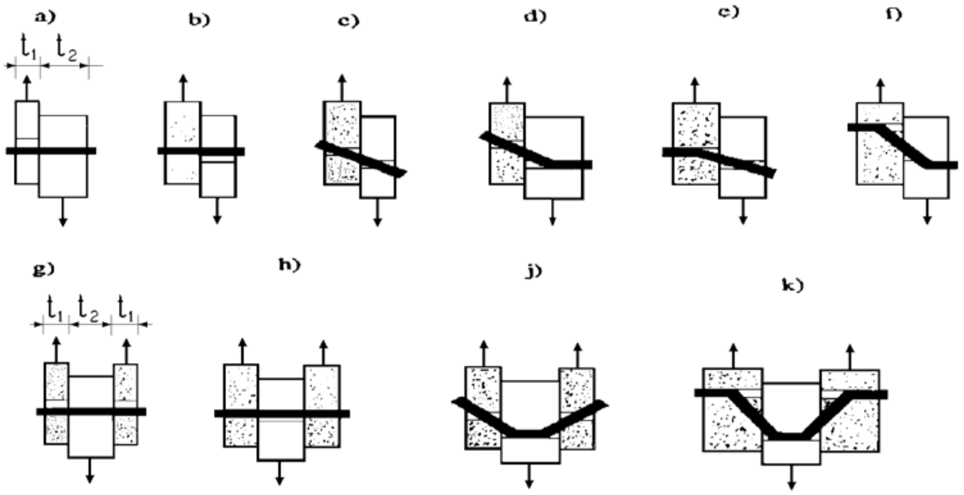

Fig. 4. Single shear and double shear connections

On the basis of Johansen's ultimate load equations the load-bearing capacities of single and double shear timber-to-timber as well as steel-to-timber connections are derived. It is assumed that the fastener and the timber are ideal rigid-plastic materials.

For design value of load bearing capacity of the fastener per shear plane in single shear connection type timber-timber loaded perpendicular in relation to axe direction of the fastener, it is necessary to take the lowest value calculated from fallowing expressions:

$$R_d = \min \begin{cases} f_{h,1,d} t_1 d & (11a) \\ f_{h,2,d} t_2 d & (11b) \\ \dfrac{f_{h,1,d} t_1 d}{1+\beta}\left[\sqrt{\beta + 2\beta^2\left[1+\dfrac{t_2}{t_1}+\left(\dfrac{t_2}{t_1}\right)^2\right]+\beta^3\left(\dfrac{t_2}{t_1}\right)^2} - \beta\left(1+\dfrac{t_2}{t_1}\right)\right] & (11c) \\ 1{,}1\dfrac{f_{h,1,d} t_1 d}{2+\beta}\left[\sqrt{2\beta(1+\beta)+\dfrac{4\beta(2+\beta)M_{y,d}}{f_{h,1,d} d t_1^2}} - \beta\right] & (11d) \\ 1{,}1\dfrac{f_{h,1,d} t_2 d}{1+2\beta}\left[\sqrt{2\beta^2(1+\beta)+\dfrac{4\beta(1+2\beta)M_{y,d}}{f_{h,1,d} d t_2^2}} - \beta\right] & (11e) \\ 1{,}1\sqrt{\dfrac{2\beta}{1+\beta}}\sqrt{2M_{y,d} f_{h,1,d} d} & (11f) \end{cases}$$

For design value of load bearing capacity of the fastener per shear plane in double shear connection type timber-timber loaded perpendicular in relation to axe direction of the fastener, it is necessary to take the lowest value calculated from fallowing expressions:

$$R_d = \min \begin{cases} f_{h,1,d} t_1 d & (11g) \\ 0{,}5 f_{h,2,d} t_2 d\beta & (11h) \\ 1{,}1\dfrac{f_{h,1,d} t_1 d}{2+\beta}\left[\sqrt{2\beta(1+\beta)+\dfrac{4\beta(2+\beta)M_{y,d}}{f_{h,1,d} d t_1^2}} - \beta\right]. & (11j) \\ 1{,}1\sqrt{\dfrac{2\beta}{1+\beta}}\sqrt{2M_{y,d} f_{h,1,d} d} & (11k) \end{cases}$$

The following notation is used:

t_1 and t_2	timber thickness or fastener penetration,
$f_{h,1,d}$, $f_{h,2,d}$	embedding strength corresponding to t_1 or t_2, respectively,
β	relation $f_{h,2,d} / f_{h,1,d}$,
d	fastener diameter,
M_y	fastener yield moment.

Design values of the embedded strengths $f_{h,1,d}$ and $f_{h,2,d}$ need to calculate according to fallowing equations:

$$f_{h,1,d} = \frac{k_{\mathrm{mod},1} f_{h,1,k}}{\gamma_m}, \tag{12}$$

$$f_{h,1,d} = \frac{k_{\mathrm{mod},1} f_{h,1,k}}{\gamma_m} \tag{13}$$

The values of modification factor k_{mod} and partial coefficient of a material γ_m are given in table 3.1.7 and 2.3.3.2 of a ENV 1995-1-1.Eurocode 5: Design of timber structures. Part 1.1: General rules and rules for building, respectively.

Design value of a fastener yield moment needs to calculate according to fallowing expression:

$$M_{y,d} = \frac{M_{y,k}}{\gamma_m}, \tag{14}$$

For design value of load bearing capacity of the fastener per shear plane in single shear steel-to-timber connection, with thickness of steel plate, $t \leq 0{,}5d$ loaded perpendicular in relation to axe direction of the fastener, it is necessary to take the lowest value calculated from fallowing expressions:

$$R_d = \min\begin{cases} (\sqrt{2}-1) f_{h,1,d} t_1 d & \text{(15a)} \\ 1{,}1\sqrt{2M_{y,d} f_{h,1,d} d} & \text{(15b.)} \end{cases}$$

For the thickness of steel plate, $t > d$, to use next expressions in the same sense:

$$R_d = \min\begin{cases} (\sqrt{2}-1) f_{h,1,d} t_1 d & \text{(15c)} \\ 1{,}1\sqrt{2M_{y,d} f_{h,1,d} d} & \text{(15d)} \end{cases}.$$

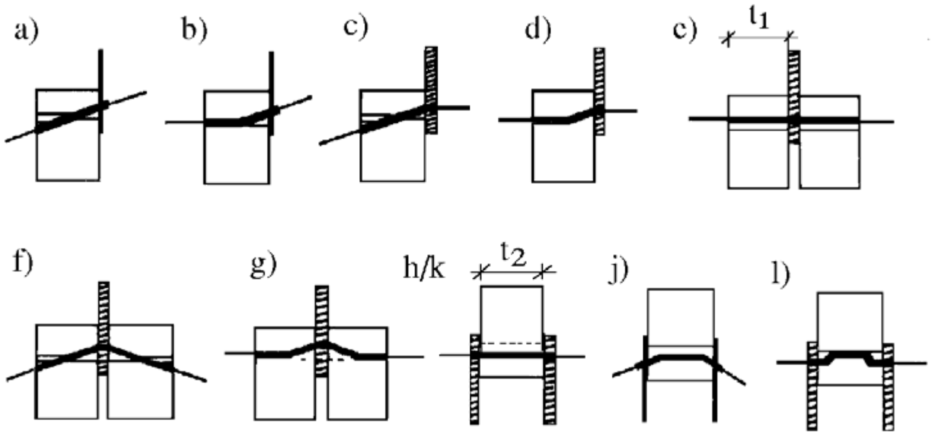

Fig. 5. Single shear and double shear steel plate-to-timber connections

For design value of load bearing capacity of the fastener per shear plane in double shear steel-to-timber connection, where the thick steel plate is between timber elements, loaded perpendicular in relation to axe direction of the fastener, it is necessary to take the lowest value calculated from fallowing expressions:

$$R_d = \min\begin{cases} 1{,}1 f_{h,1,d} t_1 d & (15e) \\ 1{,}1 f_{h,1,d} t_1 d\left(\sqrt{2+\dfrac{4M_{y,d}}{f_{h,1,d} d t_1^2}}-1\right) & (15f) \\ 1{,}5\sqrt{2M_{y,d} f_{h,1,d} d} & (15g) \end{cases}.$$

For design value of load bearing capacity of the fastener per shear plane in double shear steel-to-timber connection, where both thick steel plates are outward (figure 5h,j) loaded perpendicular in relation to axe direction of the fastener, it is necessary to take the lowest value calculated from fallowing expressions:

$$R_d = \min\begin{cases} 0{,}5 f_{h,2,d} t_2 d & (15h) \\ 1{,}1\sqrt{2M_{y,d} f_{h,1,d} d} & (15j) \end{cases}.$$

Thanks to given expressions, above and details and rules for embedding bolts and dowels in considered connections, below, now there are all needed elements for design of footbridge in regard of this point of structure. α is angle between force and grain direction.

3. Modulus of sleeping of the composite timber-concrete connection

Because of timber properties, it is not possible to make rigid connection between timber and concrete by fasteners, except by gluing. Rigidity of timber-concrete joints can be characterized by modulus of sleeping determined on the base experimental results given certain performed procedures according EN 26891.

Generally, the modulus of sleeping, C, can be described as relation of force F and inducing unit displacement of a connection δ or can be expressed as tangential or secant in regards of certain level of loading or defined displacement value of a connection.

$$C = \frac{F}{\delta} \tag{3.1}$$

Further, it has to noted that thanks to many investigations is, globally, conducted, that the value of modulus of sleeping depends on:

- the properties of coupled materials as modulus of elasticity of a timber and concrete, characteristic strengths, humidity of a timber, temperature etc.,
- kind of elements for coupling, its properties, stiffness,
- geometrical properties of cross sections coupled materials,
- experimental method.

Typical behaviour of connection in sense of modelling of sleeping under increasing loading can be described by diagram shown on the figure 3.1.

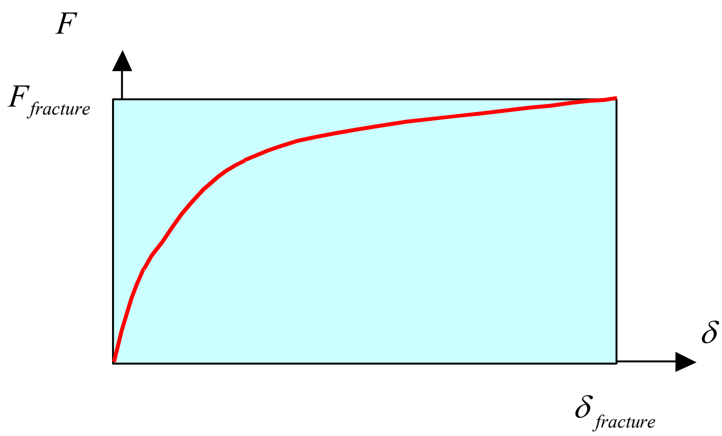

Fig. 3.1 Definition of modulus sleeping C.

On the base experiments with timber-concrete connections formed from concrete tooth and fasteners reinforcement steel, performed according to EN 26891 by Werner, for design of load bearing capacity of connection, modulus of sleeping can be calculated as:

$$C_{\sigma} = 0{,}6F_{\max} / \delta_{0,6} \tag{3.2}$$

where:

F_{max} maximal experiment force

$\delta_{0,6}$ displacement with 60% of maximal force P_{max}.

For design of deformation, modulus of sleeping can be calculated as:

$$C_{\delta} = 0{,}6F_{est} / \delta_{0,4} \tag{3.3}$$

where:

F_{est} estimated maximal experiment force, according to EN 26891,

$\delta_{0,4}$ displacement with 40% of maximal estimated force P_{max}.

From practical point of view new-fashioned design according to Eurocode5, part relates to serviceability limit states, initial value of modulus of sleeping denoted as K_{ser} can be determined, depending on characteristic density values of connected materials, $\rho_{k,1}$ and $\rho_{k,2}$ and diameter of fastener d, by equations:

$$K_{ser} = \rho_k^{1,5} d / 20 \quad \text{for bolts and dowels,} \tag{3.4}$$

$$\rho_k = \sqrt{\rho_{k,1} \cdot \rho_{k,2}} \tag{3.5}$$

Final value of displacement of connection u_{fin} consisting from materials characterized by different properties of creeping $k_{def,1}$ and $k_{def,2}$ can be determined according to:

$$u_{fin} = u_{inst} \sqrt{(1 + k_{def,1}) \cdot (1 + k_{def,2})}\ , \tag{3.6}$$

where, initial elastically displacement can be calculated as:

$$u_{inst} = 1mm + F / K_{ser} \tag{3.7}$$

For design of fasteners and elements of timber-concrete connection, according to ultimate limit states, modulus of sleeping need to calculate on the base fallowing expression:

$$K_u = 2K_{ser} / 3\ . \tag{3.8}$$

4. CONCLUSION

This paper deals with very important elements which we need for calculation and projecting connections between structural timber elements, specially, for connecting two different materials like timber and concrete. New fashioned design concept, Eurocod 5, based on the ultimate limit states and serviceability limit states, here is applied. By combining timber and concrete in new type of composite material and using thr best properties both materials, the high tensile strength of a timber and th ehigh compressive strength of a concrete, depending of different building conditions, we can find a lot of reasons for decision to apply this type of structure in comparison to concrete or steel structure.

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PRORAČUN VEZA U SPREGNUTIM KONSTRUKCIJAMA TIPA DRVO-BETON

Dragoslav Stojić, Radovan Cvetković

U radu su analizirane spregnute konstrukcije tipa drvo-beton. Kombinovanjem drveta i betona dobija se novi tip spregnutog materijala u kome se koriste najbolja svojstva oba materijala- visoka čvrstoća na zatezanje drveta i visoka čvrtoća na pritisak betona. U zavisnosti od različitih uslova građenja, postoji mnogo razloga za upotrebu spregnutih konstrukcija tipa drvo-beton u odnosu na mogućnost primene čelika ili betona. U radu su dati proračunski postupci za određenje nosivosti štapastih spojnih sredstava, veoma često korišćenih kao element za spajanje drveta i betona. Proračunski postupci su predstavljeni i objašnjeni u skladu sa novim računskim konceptom baziranom na graničnim stanjima nosuvosti i upotrebljivosti , tj Evrokodom 5. Računske jednačine u Evrokodu 5 izvedene na osnovu Johansenove teorije loma, bazirane su na kruto-plastičnom ponašanju štapastih spojnih sredstava pri savijanju, pritisku po omotaču rupe u drvetu vrednosti momenta tečenja spojnog sredstva.