Design of wood-concrete composite beams under deck bridge – Theoretical developments and construction examples

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Summary

Long ago forgotten, wood must find again all its place in the field of construction, especially in bridges. In France, a design guide is being drafting to propose a design of road bridge associating wood and concrete in a composite behaviour, via a mechanical connection. It also constitutes an implementation guide of Eurocode 5 for the justification of the wood sections and the wood/concrete connection. Composite behaviour offers the characteristic to be assured by a connection that, with usually technologies employed, authorizes a relative displacement of materials at their interface. This behaviour is rather atypical in civil engineering structures and it appeared useful to formalize the laws of behaviour that describe this kind of composite beam. Analytical and truss-girder models are made to determine internal efforts in materials, according to the rigidity of connection. At least, three recent constructions inspired by the studies of the working group are described.

Keywords: bridge, composite, concrete, wood, connection, analytical model, examples.

1. New concept: low carbon consumption bridge

1.1 Wood in France

With 16.7 million hectares of forests, in progress of 0.7% per year in the last 30 years, France is the third country in Europe following Sweden and Finland [1]. French forest is majority private-owned (75%) and is mainly deciduous (67%) [1]. Wood industry represents about 440,000 direct and indirect jobs and an annual turnover of 60 billion euros. If wood is more and more used as a construction material for buildings (new or rehabilitation), it is still superseded by concrete or steel in bridges construction.

1.2 Timber bridges in France

In the 1990s and the 2000s, several timber road bridges have been built in France. Some examples are:

- the bridge on the Dore river (Fig. 1), located in Auvergne built in 1994;
- the Merle bridge (Fig. 2), located in Limousin; structure is a timber frame with a non-

connected concrete deck (1999);

- the Crest bridge (Fig. 3), located in Rhônes-Alpes; the longest timber bridge with 92m long (2001);
- the Avoudrey bridge (Fig. 4), located in Franche-Comté, built in 2005.

Fig. 1 Bridge on the Dore river

Fig. 2 Merle bridge

Fig. 3 Crest bridge

Fig. 4 Avoudrey bridge

All these bridges have unique design and contain many fasteners and humidity exposed surfaces. Development of timber bridges in France cannot only lie on such architectural designs that requires heavier ongoing monitoring and maintenance than common structures.

1.3 Presentation of the Cerema concept

At the end of 2000s, Setra created a working group in order to promote the development of timber bridges construction in France by giving to the different actors (building owners, project managers, engineering consultants and building companies) all the necessary tools for a perfect design and sustainable structures. The working group immediately approved the choice of simplicity with wood beams connected to a concrete slab and set the following goals: design a typical wood bridge, completely calculated with Eurocodes and at a competitive cost.

1.3.1 Cross section

The deck is a composite wood/concrete structure made up with longitudinal wood ribs, connected with concrete slab and without any bracing (Fig. 5 & 6).

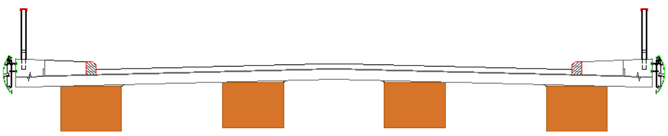


Fig. 5 Cross section

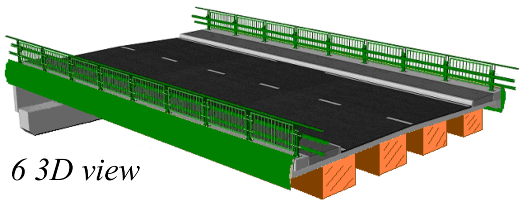


Fig. 6 3D view

The scope of use is one span bridges with a range from 10 to 20m, for road bridges above rivers or other roads. Bridges of a total length of 35 to 40m with two continuous spans are also achievable. Concrete slab has a good compressive strength and ensure protection of the wood frame from bad weather. The length of the slab's overhangs must be equal or above the height of wood ribs. The slenderness ratio of wood ribs is about 1/15° to 1/18°. Therefore, ribs' height is about 1m to 1.20m. Their number depends on the deck width (from 2 ribs for 6m deck width to 5 ribs for 14m deck width). The ribs are block-glued glulam made with 4 to 5 glued laminated girders according to French standard NF EN 14080:2013 [2], so that perimeter exposed to humidity is divided by 4. This provides high torsion stability, better loads spreading into wood, better impact resistance and no bracing at all.

1.3.2 Deck's end

Deck's end has been designed as a semi-integral abutment (Fig. 7) so that wood ribs are fully protected against water leaking by expansion joints. This design also enables:

- to locally strengthen slab against heavy trucks arriving on bridge;
- to transmit the lateral forces applied on the deck to the bearings (wind and seismic effects);
- to eliminate assemblies between support beams and a potential end cross-beam.

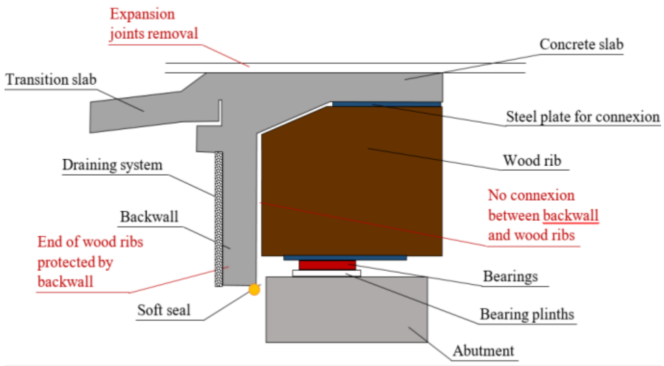


Fig. 7 Semi-integral abutment

1.3.3 Connection

Connection between concrete slab and timber ribs (Fig. 8 & 9) consists in three elements: studs, steel plates and screws. Studs generally have a 16mm diameter and are designed according Eurocode 4 [3]. Studs are welded on a steel plate with a thickness greater than external screws diameter. Screws are designed according to Eurocode 5 [4].

Fig. 8 View of studs welded on steel plate with screws before screwing

Fig. 9 View of connection after screwing

2. New concept: low carbon consumption bridge

2.1 General principles

The justifications for dimensioning this wood/concrete composite bridge concept are based on the formalism of Eurocodes and in particular of Eurocode 5. Because of the choices made for the construction layouts (in particular the protection brought by the overhang and the semi-integral abutment), wood can generally be affected in use class 2 according to standard NF EN 335 [5]. This represents most of cases for bridge built in Metropolitan France. Wood is affected to service class 2 according to standard NF EN 1995-1-1, when its average moisture is stabilized from 13 to 20%.

The principal checks specific to such a bridge concern:

- justifications of the composite sections under positive bending moment (bottom tension fibre) where wood works in bending and traction;
- justifications, if necessary, of composite sections under negative bending moment at support (top tension fibre) where wood works in bending and compression; in these sections, concrete is cracked in the global analysis model and the reinforcement bars contribute to the mechanical resistance;
- justifications under shear force and torsion in wooden beams;
- wood's justification with respect to transverse compression on support; this justification is made either according to the recommendations of technical approvals of the products or in reference to the literature on subject [6];

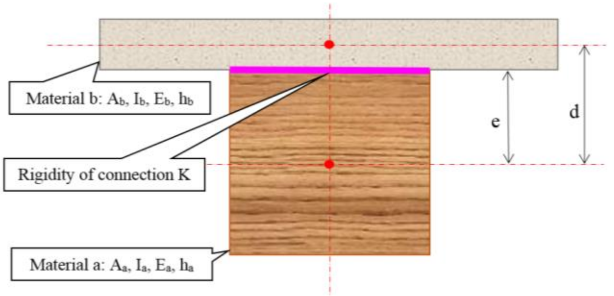
- justifications of shear connection.

Wood-concrete connection ensured by a mechanical system generally authorizes a relative displacement at the material's interface. It is called a partial connection and its rigidity affects the efforts distribution in materials. So, it must be considered for the justification of connection itself.

Appendix B (informative) of standard NF EN 1995-1-1 [4] suggests a solution (known under the name of Heimeshoff solution) in the case of a load applied to a composite isostatic beam with partial connection generating one moment that varies in a sinusoidal or parabolic way. It nevertheless appeared useful to formalize the constitutive laws for different static diagrams of structures and for more general cases of loading, and then for developing an adapted mechanical model. These developments are successively presented in the following chapters.

2.2 Analytical model of behaviour of a composite section with partial connection

We consider a beam made up of two different materials linked by a partial connection and subjected to load which generate bending (Fig. 10).



A is the section, I the inertia, E the elasticity module, h the height of each element

d is the distance between the centres of gravity of the two materials;

e is the distance between the centre of gravity of the section of "a" material and the interface between the two sections

Fig. 10 Characteristic parameters of a composite section with a partial connection

This beam undergoes bending moment. We consider a beam section at a distance X from left support (Fig. 11). This section is subject to an internal bending and normal forces in the two materials (Fig. 12).

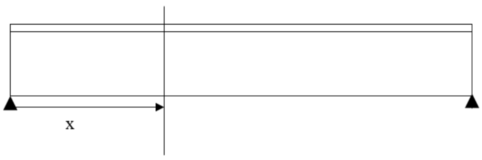
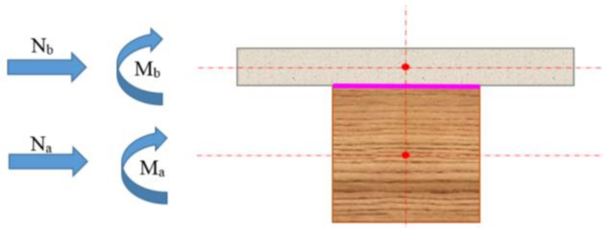


Fig. 11 Location of a section within an isostatic beam subjected to bending



N_a, M_a: respectively normal force and moment interns of material a

N_b, M_b: respectively normal force and moment interns of material b

Fig. 12 Internal forces in the section

With a single external bending moment, the equilibrium conditions of the section are as follows:

- condition 1: zero-sum of forces;
- condition 2: zero-sum of bending moments;
- condition 3: curvature is the same for the two elements (Navier assumption);
- condition 4: at the interface of the two materials, a longitudinal slip appears in link with the stiffness of connection K and the normal force transmitted N by this interface.

Given these conditions, the differential equation (1) governing the normal effort N(x) in the centre of gravity of the "b" element (equal in absolute value to the normal effort in the centre of gravity of "a" element) is written in the following form:

$$\frac{\partial^2 N}{\partial x^2} - AN = -BM \tag{1}$$

where:

$$A = K\left[\frac{1}{E_a A_a} + \frac{1}{E_b A_b} + \frac{d^2}{(E_a I_a + E_b I_b)}\right] \quad (2)$$

$$B = \frac{Kd}{[E_a I_a + E_b I_b]} \quad (3)$$

and M = M(x), bending moment in the section with X-coordinate x of the beam.

Instead of external moment bending imposed, it is possible to consider the case of a deformation imposed by one of two materials, such as for example concrete's shrinkage or temperature variations effect with materials having different expansion coefficients. The four equilibrium conditions in the section provide following differential equation:

$$\frac{\partial^2 N}{\partial x^2} - AN = K\varepsilon \quad (4)$$

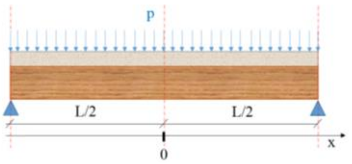
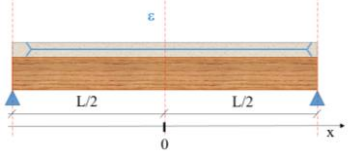
where ε is "b" element internal deformation.

In case of indeterminate structure (continuous spans), restraint deformation of the structure, as a result of imposed deformation, leads to indeterminate support reactions, therefore to one indeterminate bending moment M.

The differential equation (4) becomes:

$$\frac{\partial^2 N}{\partial x^2} - AN = K\varepsilon - BM \quad (5)$$

The table below gives the form of the solution describing the normal effort N(x) in the case of an isostatic beam with one span (Fig. 13) subjected to a load uniformly distributed or an imposed deformation of the material "b".

Uniformly distributed load	Imposed deformation of material "b"
	
$N(x) = \frac{Bp}{A}\left[-\frac{x^2}{2} + \left(\frac{L^2}{8} - \frac{1}{8}\right) + \frac{ch(\sqrt{A}.x)}{A.ch(\sqrt{A}.\frac{L}{2})}\right]$ (6)	$N(x) = \frac{-K.\varepsilon}{A}\left[1 - \frac{ch(\sqrt{A}.x)}{ch(\sqrt{A}.\frac{L}{2})}\right]$ (7)
Fig. 13 Solutions in the case of one isostatic span	

The solutions in the case of two continuous equal spans were also developed.

2.3 Truss-girder model of a composite beam with partial connection

A truss-girder model with vertical stems has been developed to integrate a connection rigidity variation along the beam. It is also possible to modify this rigidity according to the connection load level. This modification involves the definition of a nonlinear constitutive law of the connection (Fig. 14) and a certain ductility of connection (Fig 15). The constitutive law can be given using push-out tests in laboratory [7], [8], [9].

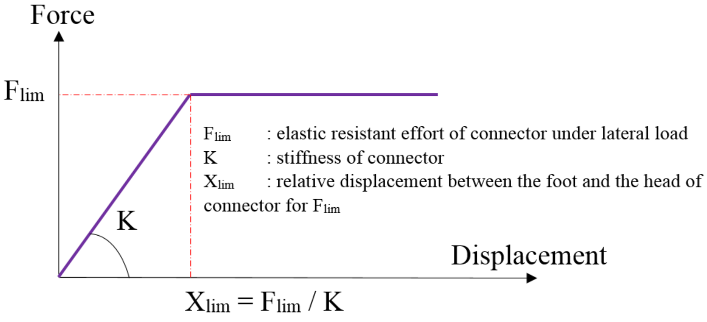


Fig. 14 Nonlinear elastoplastic law modelling the stiffness of connection

Fig. 15 Ductility due to the formation of 2 plastic hinging on the stem of the screws [9]

Concrete slab and wooden beam constitute the two strands of the ladder. The ladder rungs are the connection; their concrete side end is hinged (Fig. 16). To simulate connection stiffness, shear resistant area of the rungs is given the adequate characteristic, normal section and inertia being taken with very large values.

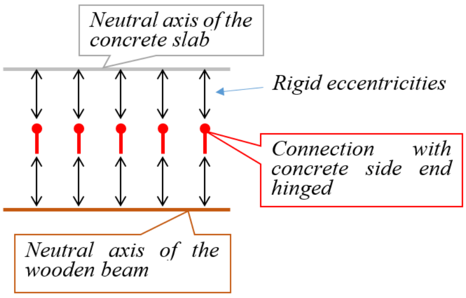


Fig. 16 Principle of the model of the lattice beam

The model takes into account connection rigidity by adapting the shear resistant area of the connection bars. Indeed, the shear strain δ at the top of a beam of length L, embedded at its base and subjected to a force F, is given by:

$$\delta = \frac{F.L}{G.S_y} \qquad (8)$$

where G is the shear modulus of material and S_y the shear resistance area.

2.4 Applications to simple cases

The comparison of the two models (analytic and truss-girder) shows a perfect identity of the results on simple cases.

For illustration, we give hereafter the graphic curve of the connection deformations obtained with the truss-girder model of a two continuous spans equal 15 m length. Cracked concrete slab is not considered here. Figure 17 shows section characteristics. Figure 18 gives strains in the case of uniformly distributed load and figure 19 shows strains due to concrete shrinkage.

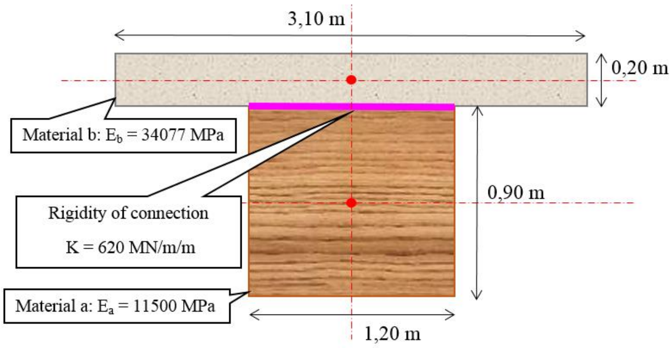


Fig. 17 Characteristic of the studied beam

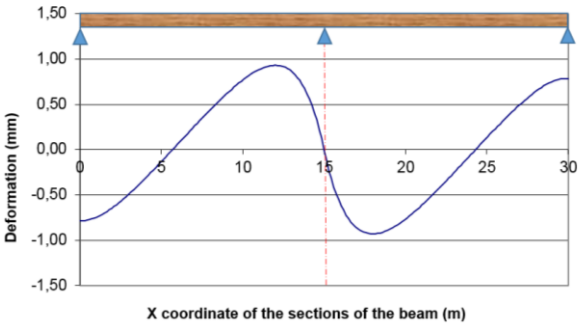


Fig. 18 Deformation of connection – Continued beam on two supports – Uniformly distributed load p=0,1 MN/m

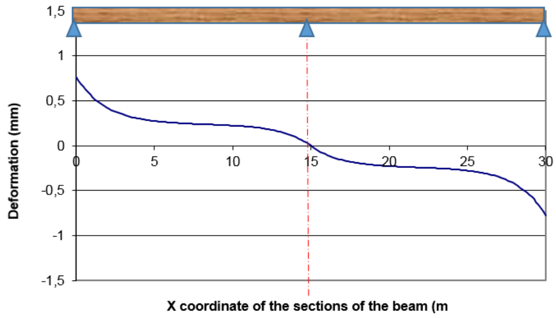


Fig. 19 Deformation of connection – Continued beam on two supports – Shrinkage of concrete $\varepsilon = -3.10^{-4}$

3. Construction examples

We present here three examples of wood-concrete composite bridges, with a mechanical connection, recently built in France, based on the concept presented at the paragraph 1.3. and for which Cerema brought its technical assistance.

3.1 Riou Valley Bridge

The companies Campenon Bernard and Arbonis built the bridge upon the small valley of the Riou near Lantosque in 2015, under the project management of Nice Côte d'Azur Metropole. The bridge carries a metropolitan road with one traffic lane. The deck presents a span of 13 m long for a total width of 6.13 m. It consists of 4 Douglas glulam ribs under the slab (Fig. 20). Each rib has a section of 0.82 m (w) x 0.90 m (h) and is made of 4 glulam beams of 20.5 cm width. Ribs received a protective treatment and a wood stain.

Fig. 20 View of the 4 girders

Connection consists of steel plates 190 mm x 346 mm in plan and 12 mm thick, positioned in reserved spaces dug in beams (Fig. 21). 16 mm diameter studs (6 studs per plate) are welded to superior faces of steel plates, which are bonded to the beams with WURTH VG 12 mm x 140 mm, screws (28 screws per plate). Beams rest on reinforced elastomeric bearings. Beam supports are strengthened with grill of reinforcing screws (SFS WR T 13 500 mm length). A crane placed the ribs on the abutments. There is no bracing at all between ribs. Slab is made of C35 concrete precast segments (Fig. 22), with a thickness of 25 cm. Each segment has four slab connection recesses where studs are concentrated.

Fig. 21 Reserved spaces dug in beam

Fig. 22 Precast segments for the slab

3.2 Cognin bridge

The companies Eiffage and Pierrefeu built the bridge upon the Hyeres River in Cognin in 2015 under the project management of Chambéry Métropole. Bonnard and Gardel design office was project manager for construction works, based on the project designed by the consulting engineer CBS. The bridge carries a secondary road with two traffic lanes and a wide cycle track. The deck presents 3 continuous spans, respectively 9, 19 and 10 m length, for a total width of 12.74 m (Fig. 23). It consists of nine glued laminated ribs in Douglas under the slab (Fig. 24) whose section is 0.54 m (w) x 1.00 m (h). Each rib is made of three glulam beams, 18 cm wide each. Ribs received a protective treatment and a wood stain.

Fig. 23 Lateral view of bridge

Fig. 24 Intrados view of deck

Connection (Fig. 25) is made of steel plates (200 mm x 400 mm in plan and 10 mm thick). Studs 19 mm in diameter (4 or 5 studs per plate depending on areas) are welded to superior faces of steel plates which are bonded to the beams with SFS WR T 13 mm x 400 mm screws (20 to 23 screws per plate depending on the areas). A crane put ribs in place, braced together on every support axis (Fig. 26). They rest on reinforced elastomeric bearings and their support zones are strengthened with grill of reinforcing SFS WR T 13, 500 mm length screws on abutments and 600 mm length on piers.

Fig. 25 Beams with metal plates for connection

Normal concrete class C35 is used for the reinforced slab, 25 cm thick, cast-in-place on sacrificial wood formworks (Fig. 27). The beams are supported by semi-integral abutments with hinged transition slab.

Fig. 26 Bracing on pier

Fig. 27 Casting of the slab

3.3 Large wildlife bridge on RN19

The PS12 over RN19 in Lure was built by the companies Eiffage and Arbonis in 2017 under the project management of “Direction Régionale de l’Environnement de l’Aménagement et du Logement de Bourgogne - Franche-Comté”. “Direction Interdépartementale des Routes Est” was project manager for construction works. The bridge spans a forest path and assures ecological continuity for large animals. The deck presents 2 continuous spans 15 m length each for a total width of 12.60 m. It consists of four glued laminated ribs in Douglas under the slab whose section is 1.20 m (w) x 1.00 m (h). Each rib (Fig. 28), 31.40 m length, is made of 6 glulam beams 20 cm wide (Fig. 29). Beams received a protective treatment and a wood stain.

Fig. 28 Beam in workshop

Fig. 29 Gluing of the little beams

Connection (Fig. 30) is made of steel plates (550 mm x 550 mm in plan and 10 mm thick). Studs 16 mm in diameter (9 studs per plate) are welded to superior faces of metal plates which are bonded to the beams with ROTHOBLASS HBS 12 mm x 160 to 320 mm screws (66 screws per plate).

Fig. 30 Girder with connection

Beams are put in place with a crane (Fig. 31), without any bracing. They rest on reinforced elastomeric bearings (Fig. 32) and their support zones are strengthened with grill of reinforcing screws (SFS WR T 13, 600 mm length). Normal concrete class C35 is used for reinforced slab, 20 cm thick, cast-in-place on general shoring supporting wood ribs too. Ribs are supported by semi-integral abutments.

Fig. 31 Beams being put in place with the crane

Fig. 32 Support plates and reinforced elastomeric bearings

4. Conclusions

Wood is a natural material with very interesting mechanical characteristics. It must find in the field of construction all its place, and especially in the field of road bridges.

In this context, Cerema is working on the drafting of a guide for the design of a wood-concrete composite bridge with a mechanical connection. The aim is to help the designer at all stages of the project from the general design to the detailed design. To make reliable the good constructive dispositions that govern a sustainable structure, the guide is based on experiments made during the construction of real works

Beyond allowing a composite behaviour, the advantage of the connection is to ensure the durability at the interface between the two materials. The connection system must be sufficiently flexible and ductile to dampen the anchoring of the imposed deformations and to allow redistributions.

The periodic monitoring of newly constructed structures may, if necessary, lead to proposals for amendments or additions.

5. Acknowledgements

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