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New concepts for timber bridge decks without cross beams: Stress laminated decks and interlocked laminated decks

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1 Introduction

Timber bridge decks have been built for long period of time with transversal planks. In the US, nailed laminated decks were built from the 1920's to mid 1960's. Flat laying glulam beams sometimes connected with dowels were used before the stress-laminated timber decks were introduced in the Ontario Highway Bridge Design Code in 1976 [5].

The introduction of the stress lamination technique in the 1970's represented a significant renewal of timber bridge building. Since then, significant improvements have been made with respect to materials and structural protection. However, little progress has been made in the area of structural design. In this paper two attempts to introduce new ideas in the structural design of timber bridges are presented: one with the purpose to eliminate the losses of stress by using unstressed bars and one with the purpose of reducing the amount of steel and increase clearance below the bridge by omitting cross beams.

2 Evolvement of stress laminated timber decks in Norway

Stress laminated timber bridge decks evolved in the 70th in Canada and the US. In Norway these have been built since the 90s. Before about 2005 most bridges were built using planks of 233 mm depth, typically stressed with 18 mm high-strength steel bars. Since 2005 new load models introduced by the Eurocodes made it difficult for road bridges to handle the loads using planks and thus glulam beams were introduced instead. Greater spans were, hence, possible and glulam beams are now dominating pedestrian bridges as well.

Because of issues with corrosion, grease incapsulated steel strands have been introduced instead of bars and have been used on several bridges lately. The stressing system should ideally be with a low E-modulus and high strength to ensure little stress loss by later shrinkage and creep effects. Steel strands have some advantages here, but other materials such as fibre composite rods have been tried and reportedly also so in Canada. Up to this date these are however still in development.

The deck structure is most often a secondary superstructure connected through cross beams to a primary superstructure. In the design of Evenstad Bridge, back in the start of the 90's, various systems for lateral support of arch girder were investigated. Case studies were made of both a sideways stiffening system at the supports and by a stiff connection to the cross beams. Evenstad Bridge was at the time the first large road bridge constructed in Norway for several decades, comprising of 5 equal spans of bow trusses with a total length of 180 m. The use of cross beams of steel was found to be the most efficient solution, though the wish to use more timber was strong. Cross beams of steel could be made reasonable small in depth and also function as transversal stiffening of the truss. Using timber for cross beams would make it difficult to protect the top-down connection needed, and also to achieve sufficient flexural stiffness for the connection to the superstructure. Using steel beams has since been state of the art for all corresponding projects.

The concept with simply supported timber decks on cross beams has some disadvantages when it comes to clearance below the bridge. The cross beams of road bridges are typically 500-1000 mm deep. With increased focus on gradients of the bridge approaches, solutions placing the cross beams in-between carriageways (typically on highways) or between railway tracks has been done on several projects, though with the downside of none-optimal spacing and even using beams with various angles to the deck. Using such simple static solutions may result in more complex design [4].

Another focus on timber deck structures in Norway has been on the need for re-stressing bars, which at times may be difficult due restrictions to access. Designing bridges that have such planned maintenance has been disputed as alternatives with other materials do not require this. Furthermore, the long-term stress levels of stress laminated decks and their rest-capacity has never really been explored being a momentum of unknown. It must also be said that even with these unknowns stress laminated decks have proven to work well on public roads where axel loads of 10 tons are common.

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3 Laminated decks without cross beams

3.1 General

Traditional timber bridges were provided with cross beams of timber, but modern traffic loading with heavy wheel loading required cross beams of significant depth with respect to the shear force capacity. Cross beams made of steel, however, showed to be far more efficient, and today steel material is the primary option for cross beams on timber bridges on roads with vehicle traffic.

Figure 1: Hot dip galvanized cross beams with fixing lugs for suspension post attachment

A frequent plea raised against today's timber bridges is that they contain as much steel as timber, and that the designation "timber bridge" is hardly justified. In addition, today's focus on environmental foot print has given reason to try to reduce the amount of steel as timber normally is the more environment friendly material. In this context the omission of cross beams is an obvious issue to investigate.

A stress laminated bridge deck without cross beams requires significantly more timber than with cross beams. The costs of the required additional timber will, normally, amount to a higher cost than the steel beam. It is, thus, not surprising that a concept without cross beams in most cases will be more expensive than a traditional solution. However, in an environmental and global warming context the increased use of wood instead of steel may be favourable. Another advantage by omitting the cross beams is that it will – in most cases – reduce the effective construction depth, i.e. the distance from the top surface of the deck to the lowest point of the deck. This may be of importance by bridges crossing rivers exposed to flooding. True, increased depth of the timber deck will be unfavourable, but in most cases the required depth of cross beams will increase more than the depth of the timber deck.

Figure 2: Stress laminated deck of sawn timber on steel cross beams (Måsørbrua)

As stress laminated plates are extremely orthotropic with one strong and stiff direction and one very weak direction it may seem strange to consider the transverse and weak direction for load carrying purpose. However, a local concentrated load will, to a certain extent, be carried in both directions. The distribution of load in the two main directions will depend on the main static system of the bridge. In case of, e.g., an arch bridge the load on the bridge deck may be transferred to an edge beam, while in another case, where the bridge deck constitutes the whole static system, the entire load has to be transferred in the longitudinal direction.

Arch bridges, suspension bridges and stay cable bridges may be provided with edge girders. The bridge deck will then span between the edge girders. The governing sectional forces will be the bending moment in transverse direction and shear along the edge girder. By concentrated loads like wheel loads the larger stiffness in longitudinal direction will provide a significant load distribution in that direction and a substantial reduction of the peak moment and a corresponding reduction of the shear force at the edge girder.

In case of evenly distributed load along the bridge deck this favourable effect will not be present, but there are other possibilities. The tie bars may be placed below the centre of the deck slab in order to impose a negative moment to counter the governing moment in case of stress lamination and in order to obtain an increased lever arm of internal forces in case of interlocked lamination. In addition the depth of the bridge deck may be varied such that the maximum depth will be in the middle of the deck and the required cross slope will be obtained without increasing the the non-structural dead weight of the slab.

3.2 Design principles of stress laminated bridge decks without cross beams

Bending in transverse direction, i.e. in the weak direction, will require an increased depth of the deck as well as more prestressing. One requirement for prestressing is that there shall be no tension between the laminations on the one hand and on the other hand the maximum compression transverse to fibres has to be limited. In addition, the prestressing shall be sufficient to ensure transfer of shear across the intersection between laminations.

It should be noticed that the increased depth of the deck will increase the the bending capacity in longitudinal direction as well as in transverse direction. This means that the timber is utilized for load carrying purposes in both directions, and that the increased depth of the deck allows larger spans in longitudinal direction.

The lack of cross beams may represent a problem for the erection of the bridge deck. However, it may be overcome by e.g. the use of temporary supports, scaffolding, skidding or by use of cranes.

3.3 Hemsila Footbridge in Hemsedal, Norway

A prototype bridge is designed as a footbridge crossing the river Hemsila in Hemsedal in order to demonstrate the applicability of the concept of omitting cross beams. As the valley floor is quite flat at the bridge site and the bridge had to be designed for a 200 years inundation where most of the adjacent area is flooded. Consequently, it was important to raise the road surface as little as possible while still keep the required clearance above the water level. The concept showed to be ideal in such cases.

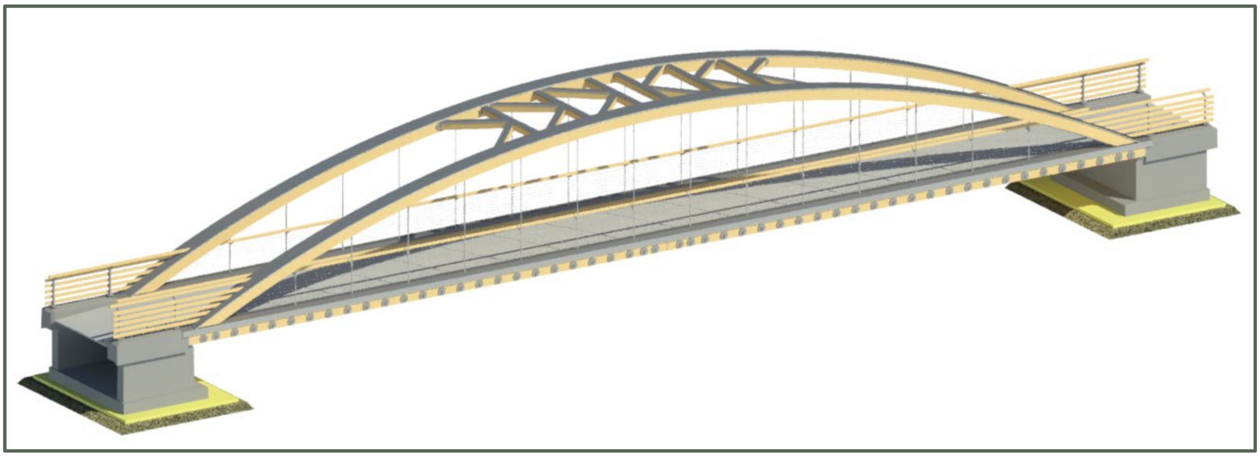

Figure 3: Hemsila Bridge, Hemsedal, Norway

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The span of the arch bridge is 33,7 m and the span of the bridge deck between suspension ties is 3,67 m. The width of the footway is 3,0 m allowing for a service vehicle. The structural design is according to Eurocode.

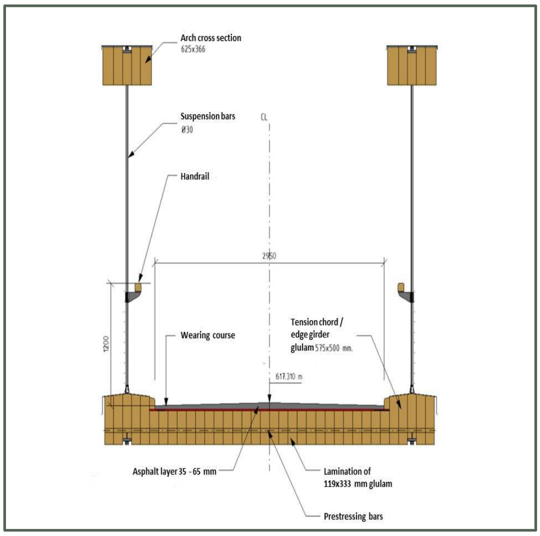

Figure 4: Cross section of Hemsila Bridge

As can be seen from the figure the possibility of increasing the depth of the lamination towards the centre of the deck in order to form the surface slope was not utilized in this case.

Structural design was performed by Sweco, Norway more than two years ago, based on a bridge concept of Dyken AS, and production of the superstructure were commenced at Moelven. However, the awarding authority got some financial problems and it was decided to complete the production of the superstructure and put the bridge project on ice. The complete superstructure is now stored at Moelven, and hopefully, the bridge may be completed this year.

Due to poor soil conditions a bowstring arch system was considered the best solution. In this particular bridge concept the edge girder was chosen to be an integrated part of the bowstring arch, acting as the tension chord. This means that the horizontal truss from the arches is taken as tension in the glulam truss and the abutments are exposed to vertical forces only.

In the case of Hemsila Footbridge the superstructure is presupposed to be assembled on a temporary rig on shore alongside the river and then turned 90 degrees and lifted in place by a mobile crane.

3.4 Road bridges without cross beams

The Hemsila Footbridge concept showed to be promising, and the idea of investigating the possibility of designing a similar road bridge without cross beams suggested itself. Test calculations on a two lane road bridge were carried out based on the Eurocode. A challenge in this context showed to be the optimization of prestressing versus the depth of the timber deck.

The design starts in transverse direction with determination of the necessary depth of the deck plate and the corresponding amount of prestressing which fulfils the requirements with respect to cracking between laminations and maximum compression transverse to fibres. When the geometry of the cross section is determined, the maximum span of the deck has to be calculated in order to utilize the timber material in both directions. It is a good design principle to utilize the material twice – if possible. However, for design criteria, such as comparison strength for two dimensional stress, and for bending stress transverse to fibre Eurocode offers no rules. The test design had to be based on simplified and conservative assumptions.

Figure 3 shows a schematic diagram of a cross section. The cross section is independent of the overall structural system. The edge girders are stressed together with the lamellas to form one unit. The edge girders are, thus, an integral part of the deck structure. The span in longitudinal direction is approximately the distance between supports by e.g. pillars or suspension rods.

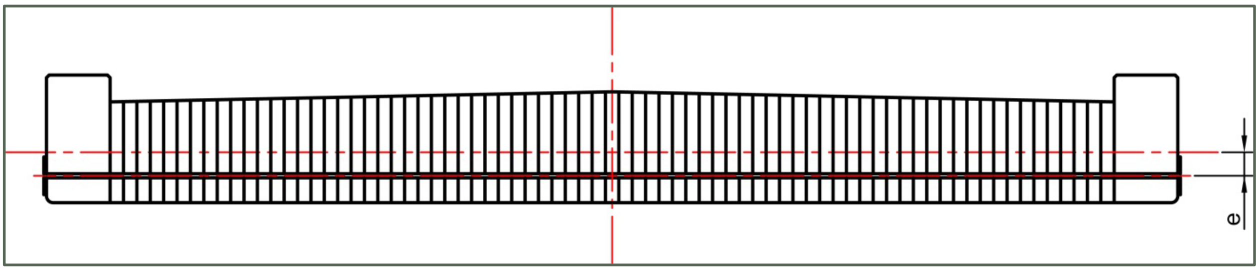

Figure 5: Cross section of a bridge deck without cross beams

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3.5 Considerations regarding loss of prestress

Loss of prestress will always be an effect which has to be considered for designs that rely on prestressing. In some cases the loss of prestress may lead to a total collapse in other cases the loss may cause local damage only or violation of serviceability requirements. It is also important distinguish between if the failure of one prestressing tendon may cause failure of the entire structure or if there are some redundancy in the system. In most cases the problem is only that the prestressing force slowly diminishes over a long period of time. In that case minor visible effects may be observed and the problem solved by restressing.

For stress laminated decks there is no serious problem if some single tendons fail as the overall integrity of the deck is not depending on a few tendons, and the broken tendons may be replaced. By a general loss of prestress due to e.g. creep and shrinkage and missing re-stressing of the tendons increased deflection or slipping between the laminations may be observed and the damage be mended relatively easy.

One may query what the effect of prestressing loss will be for a stress laminated deck without cross bars. The general effect will be about the same as for ordinary stress laminated decks. Bending in transverse direction will cause cracks to open up between the laminations at the underside of the deck and at the edge girders slip due to shear force may occur. The cracking at the underside of the deck will of course cause increased compression transverse to fibres at the top surface of the deck and possible permanent damage by local crushing.

By loss of prestress some problems may arise at butt jointed lamination. When the lamination is consisting of large glulam beams a significant amount of prestress is required in order to maintain the full bending capacity at the cross section with the butt joint. If it is considered a problem the application of slotted in gusset plates and dowels may increase the bending stiffness and capacity.

4 Interlocked Laminated Decks

Transferring shear stresses between lamellas through an interlocking shape of elements could reduce the need for pre-stressing. In order to investigate the concept, tests were conducted by a student group making hexagonal shaped elements from square timber elements /1/, having the pith close to the centre of each element. The depth of each element after sawing was 76 mm. The elements were afterwards glued together in the vertical direction. For the tests the depth was limited to two elements, or 2 half’s and one in centre, total depth of 152 mm.

Tests have shown that if using hexagonal shapes as shown in figure 4 the failure mechanism was very much ductile and no brittle shear failure was observed on any tests. In the tests the lamellas were totally restrained sideways, which might impact especially the friction between lamellas. Still, the failure mode was clearly compression perpendicular to grain from the loading block. Only after considerate deformations flexural stresses perpendicular to grain resulted in tension stresses. This came to some surprise since interlocking in shapes often has been said to be doomed due to the low rolling shear capacity of timber. This is probably dependent on the angle of the interlocking, but for the hexagonal shape clearly not an issue.

Figure 6: Shear test failure of oblique interlocked lamellae [2]

Tests were also done with a small deck to find system parameters such as the relation between transversal and longitudinal stiffness E_{90}/E_0. A deck of 0,815 m width, 3 m length and 0,152 m depth was tested with

a point load in the middle. The elements were hand-tightened together by steel rods. The deflection was measured at several points and afterwards the corresponding E-modulus was calculated by numerical software.

The tests proved transversal bearing, however with only a small relation of E_{90}/E_0 of 0,004. This might be due to several reasons. One is that the transversal stiffness is known to vary with stress level of pre-stressed decks [3]. Therefor it was no surprise that just hand-tightening did not give a stiff deck. Secondly voids between the elements probably also has a large impact on the results. However, a plate effect was proven being able to transfer shear loads corresponding to a pre-stressed deck, just not being pre-stressed.

In case of large deformations, the steel bars could experience contact pressure to the timber deck. In such cases the real load bearing strength would be increased which for accidental load situations would be positive. As is the case for pre-stressed decks, though to our knowledge not being argued for in design. By using ordinary low-strength steel this effect might be easier to design with.

Advantage of this concept is that it only requires restraining, not pre-stressing, though some pre-stressing probably has advantages when it comes to the stiffness of the deck. For instance, local unevenness's may be smoothed out. From inspection experience the prestressing of decks seem to stabilize at around 0,10-0,15 MPa which probably should be sufficient. The bars holding the deck together should not be of high-strength steel, but rather normal steel being more stiff and less flexural as there probably wouldn't be a problem of stress loss over time. Using normal steel would also ease coating protection which at times has been an issue in Norway on stressing rods.

5 Conclusive remarks

It has been proven by calculation that using the deck structure in transversal direction instead of cross beams is possible. It has also been shown by tests that interlocking shapes of deck lamellas is possible for transferring shear loads. A combination of the two might be beneficial to some projects.

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