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TIMBER FOOTBRIDGES – VALORIZATION OF PARAMETRIC ANALYSIS IN OPTIMIZATION OF LAYOUT OF BEAM BRIDGES

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Abstract. Paper presents results of the analysis of possible design solutions of timber beam bridges considering all usual demands for their stability, safety and functionality when they are designed to serve pedestrian and cyclist traffic, and, if necessary, traffic of emergency and service vehicles as well. Parametric finite element models (FEM) of bridges with simply supported glulam main-beams, have been divided into four groups, each consisting of several subgroups. The type of load-carrying deck (solid timber or CLT deck, covered by asphalt layer and protected) and its position (lower or upper) were selected as relevant characteristic for some group, while the type of transverse layout, corresponding to certain deck width and usable traffic profile, and also accompanying solution of spatial stabilization were decisive for differentiation of considered subgroups. Using the span of the straight main-beams and useful width of the load-carrying deck, conditioned by traffic requirements as input parameters, prepared FE models, classified into twelve different cases were undergone to static and dynamic analyses. According to criteria we selected as relevant, the results of performed analysis were given as recommendations for the selection of optimal structural layout matching the span of the bridge and the requests on its functionality and durability.

Keywords: timber beam bridges, cyclist and pedestrian traffic, emergency vehicle traffic, optimization criteria, parametric FEM analysis, structural design.

1. Introduction. The purpose of the preliminary parametric analysis [1] is the selection of the layout of the timber footbridge which structural form with simply supported straight main-beams could be consider as optimal for particular span and useful width of the deck. The absence of internal columns simplifies the analysis of wind loads [2], and chosen span range excludes the need for dynamic analysis due to the wind [3]. It is applicable in both urban and rural areas, and almost regardless of climate zone since it is traffic load crucial for the analysis [4, 5].

For its both characteristic, the two goals of conducted parametric analysis are set: define criteria of the analysis and evaluation of results, as well as propose solutions that would fulfil the basic demand of mechanical resistance and stability on the economic justified grounds. The results of the analysis are a proposal of the transverse layout type matching the type of the load-carrying deck, and it is suitable to variations of main-beam spans, L (from 10m to 18m) and the useful deck widths, B (from 2m to 4,5m). The following parameters were analysed: position, type and static systems of the load-carrying deck (open-boarded or sealed solid timber deck and CLT), number and the layout of main-beams and transoms (cross-beams), i.e. geometry of the T-beams with CLT flange (as alternation), and ancillary changes of the type of spatial stabilization. Structural members of standard and high strength were applied and analysed: D30 / D40 (for hardwood solid deck), and C24 / C30 (for stringers of softwood) or GL24h / GL28h (for main-beams and transoms). For the CLT decks, an even quality of the layers is considered (planks of standard strength class, C24, with thickness d = 22 mm) and the effective depth of 5-layered CLT, d = 100 mm [1].

2. Parametric analyses

2.1 Parameters, parameter choice criteria and criteria for valorisation of design solution. Optimization of the design solution (layouts) is based on the variations (Figure 1, Table 1 and Table 2) of the following parameters of the analysis: span *L*, width of the bridge *B*, type and the position of the deck together with ancillary changes of transverse layouts and spatial stabilization.

Satisfying the requirements of the intended purpose, safety and comfort of traffic, was the logical criterion of choosing the analysis parameters. Therefore, the analysed effects of the variations of totally 6 types (Table 1) were classified according to width of usable traffic profile and the number of traffic lanes on the type of the transverse layout of the bridge. Widths of 3,0m upwards enable a mixed traffic separated by lines, colour contrasts or texture separation, where separate kerbs (for types IV. and V.) or separating railings (e.g. for type VI.) for more than two traffic lanes [4, 5]. Analysed effective deck widths are defined as prescribed smallest usable traffic profiles, expanded by 0,4m, i.e. by 0,7m (for mixed traffic) in order to meet safety requirements and to provide usage comfort, in accordance with national regulations on basic conditions for public roads and cyclist infrastructure [6, 7].

Table 1 – Varied useful widths – analysed types of usable traffic profiles [1]

Type	Cases (Fig.1)	Number of traffic lanes		Useful width of the bridge [m]
		pedestrians	cyclists	
I.	1 and 7	2	0	2,0
II.	2 and 8	0	2	2,5
III	3 and 9	1	1	3,0
IV.	4 and 10	2	1	3,5
V.	5 and 11	1	2	4,0
VI.	6 and 12	2	2	4,5

The criteria of the choice of the range of span (from 10 m up to the 18 m), with the increase of 2 m represents expected widths of obstacles, limitation in the technology of production, transport and assembling, and cost-effectiveness of this type of structural form [4, 5].

The following deck types (Figure 2, Table 2) were analysed as characteristic for the defined purpose of the bridge: 1) solid timber deck, 2) CLT as countersunk deck continuously laid over transoms and 3) CLT deck as flange of glued composite with Glulam ribs, i.e. series of T-beams, as the alternative proposal of grillage assembly. The term of solid timber deck refers on planks with castellated section (grooves as anti-slip option) transversal laid over stringers (sealed, countersunk deck) or main-beams (open-boarded deck). Varying the position of the running deck implicates different solutions of providing spatial stability, as well as classification of main-beams into appropriate serviceability class (2 or 3, used in calculation) and hazard class (2 or 3, concerning durability and protection measures) [1].

Table 2 – Analysed cases classified into representative groups of FEM

Analysed FEM groups [1)]	I.[3)]	II.	III.[4)]	IV.[4)]
Type of the deck	1	2	1	3
Position of the deck [2)]	lower	lower	upper	upper
Range of deck width, [m] [2)]	≤ 3,0	≥ 3,5	≤ 3,0	≥ 3,5
Analyzed cases [2)]	1 – 3	4 – 6	7 – 9	10 – 12
[1)] shown on “Figures 3 and 4”; [2)] shown on “Figure 1” and given in “Table 1”; [3), 4)] defined subgroups that enable the number of stringers / main-beams to vary				

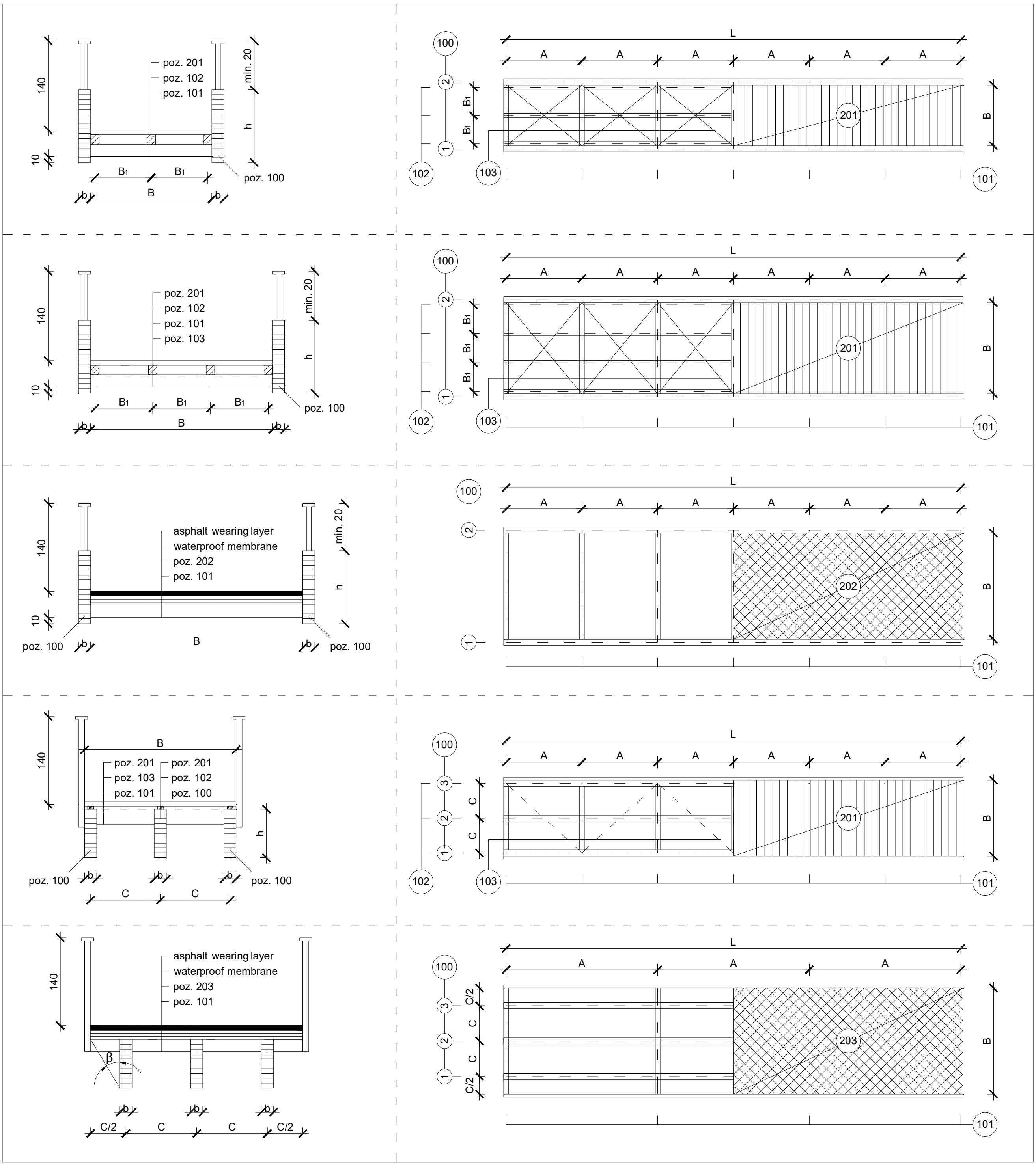
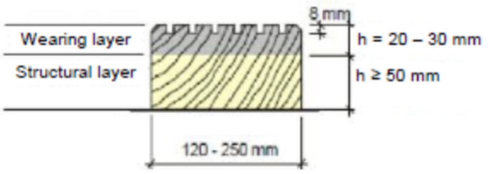
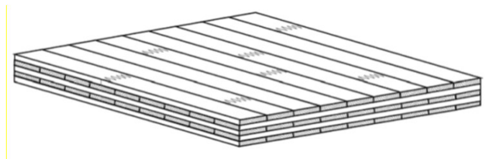


Figure 1. Schematic examples of analysed cases and accompanying groups / subgroups of FEM – varying of layout and load-carrying deck type:
a) Case 1: Group I.; b) Cases 2 – 3: Subgroup I.;
c) Cases 4 – 6: Group II.; d) Cases 7 – 9: Subgroup III.; e) Cases 10 – 12: Subgroup IV



Boards with castellated section – used for type 1)



Coated CLT decks – used for type 2) and 3)

Figure 2. Timber products used for analysed types of decks from 1) to 3 [1]

Varying the position of the running deck affected different solutions of providing spatial stability. Beside common solutions of bracings, based on triangular principle of stabilization, alternative solutions based on grillage principle were analysed for all cases with upper position of the load-carrying deck (Figure 1 and 4). Variations of the span and spatial stability solutions we achieved by altering the number of transoms and their distance (*A*). For groups III. and IV. (as defined in Table 2), the number of transoms was limited on 5, e.g. on 4 for stiffeners.

The defined initial criteria of evaluating optimality of the design solution (the type of the deck and transversal layout, the way of ensuring spatial stability, etc.) are ratios of quantities of used timber vs. span, expressed: directly (for the type of transverse layout) and indirectly (for main-beams only, considering their depth and number). Optimality of design solution has been valorised, and the sufficient mechanical resistance and stability of the entire structure had been the most important criterion. Considering the preliminary level of conducted analyse, recommendations are derived from the results of verifications of serviceability limit state only (deflections and vibrations), performed for more than 200 examples of FE models of bridges [1].

2.2 Considerations about durability and protection. The deck in first two types is replaceable, and due to direct exposure (use class 3), requires adequate strategy of surface or preservative treatment, drainage system and sealing. It is particularly valid for CLT, and therefore additional wetting prevention (layers of waterproofing membrane and hydro-insulation) beneath the wearing asphalt course needs to be used together with replaceable side cladding or strips. With this the presumption only, CTL might be classified in serviceability class 2 (prerequisite of its structural use). For 3) type, a special strategy of treatment needs to be applied because all parts of the assembly are structural member, irreplaceable within designed working life. Necessary treatment of the main-beams as vital members must be applied in all considered cases: good protective design details, corrosion-resistant metal cover, surface finishes, etc. In all cases with the upper position of the deck, where it acts as “roof”, main-beams are “drawn in”, and angle ß ≥ 30 (Figure 1) enables protection from rainfall, while side wooden strips provide additional protection. Side faces of exposed main-beams might be cladded by shiplap boards or louvers [5, 8]. Within conducted analyse we covered influence of only those protection measures that affect the increase of permanent load. The effects of costs of implementing a protection strategy were out of scope of our investigation, although for partly exposed vital members, they can be initially estimated in amount of 10% up to 15% of total costs [5].

2.3 Finite element models (FEM) groups subjected to static and dynamic analyses. FEM analysis were conducted for the influence of self-weight (using software package, including the effects of varying of cross-sections), permanent load (e.g. concentrated load due to parapet and uniform loads of wearing layer, applying its thickness of 30 mm for grooved surface of planks, and 50 mm for asphalt finishing and waterproofing layers above CLT), variable loads of snow (with s 2,5 kN/m^2) and wind (with its basic velocity of 25 m/s, characteristic for the continental area) were also considered. Vertical traffic load (pedestrian) was applied as 5,0 kN/m^2, where favourable effects due to the span above 10 m were disregarded [3], and horizontal as 10% of amount of the vertical load. The vehicle traffic was modelled as the moving load, considering its position variations inside the usable traffic profile and tracking (Figure 3). National norms HRN EN 1995-1-1 and HRN 1995-2 were applied in conjunction with norms HRN EN 1990 and norms HRN EN 1991-3, HRN 1991-4 and HRN EN 1991-2 (for load analyses) and their National Annexes (valid in The Republic of Croatia).

For every considered type of the transverse layout and accompanying solution of spatial stability (Figure 1) appropriate 3D FEM was prepared. Using altogether 4 basic groups and relevant sub-groups of these spatial models were prepared in order to check the instantaneous and the final deflection (using relevant stiffness properties and load combinations), for checking the deflection due the vehicle (as an independent load). The same 3D FEM-s were subjected to dynamic analyses to determine the vibrations due pedestrians and combined influences of self-weight and permanent loads. Sub-models were designed to analyse the influence of moving load, calculating the deflection of planked deck where the number and cross-section of stringers were varied for its maximal distance of 1m. Horizontal load was applied as 60% of vertical moving load.

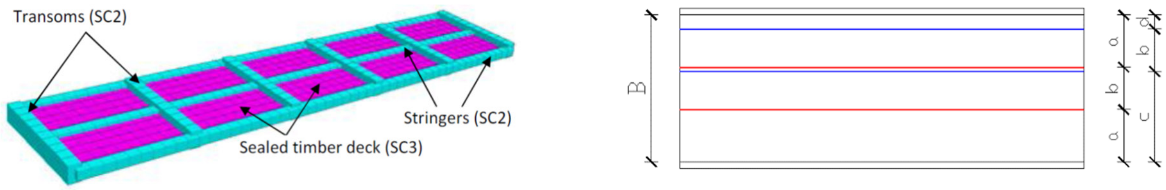


Figure 3. Example of submodel for static analysis of the deck (left), and simulation of moving load with traced position of the vehicle (*b* = 1,3 m) [1]

All prepared FEM-s (Figure 4) were analysed with span variations. For systems with countersunk deck, grid of the transoms was followed by the increase in span, while for the systems with upper deck position, the number of rectangular glulam main-beams (group III.) or composite T-beams (group IV.) were varied from 3 to 4, using suitable subgroups of FEM-s. FE models of IV. group were modelled with simplification, applying the bending stiffness $(EI)_{ef}$ calculated for glued composites, presuming so the full composite action of those T-beams. In order to facilitate the valorisation of the effects of the application of a certain type of transverse disposition, the cross-sections of structural members other than main-beams were set as constant (i.e. 200/300 mm for glulam transoms, 160/240mm for softwood stiffeners (in grillage systems), and 160/160 mm for stringers), wherein load-carrying section of 200/50 mm was used for planked decks, and effective thickness of 60 mm for CLT decks. It should be noted that 5-layered CLT plate was modelled as 3-layered only, neglecting the load-carrying contribution of its transverse layers and taking them into account through increased permanent load. In addition, verification of the deflection for sealed planked deck wider than 2 m passed the system with two inner supports (stringers).

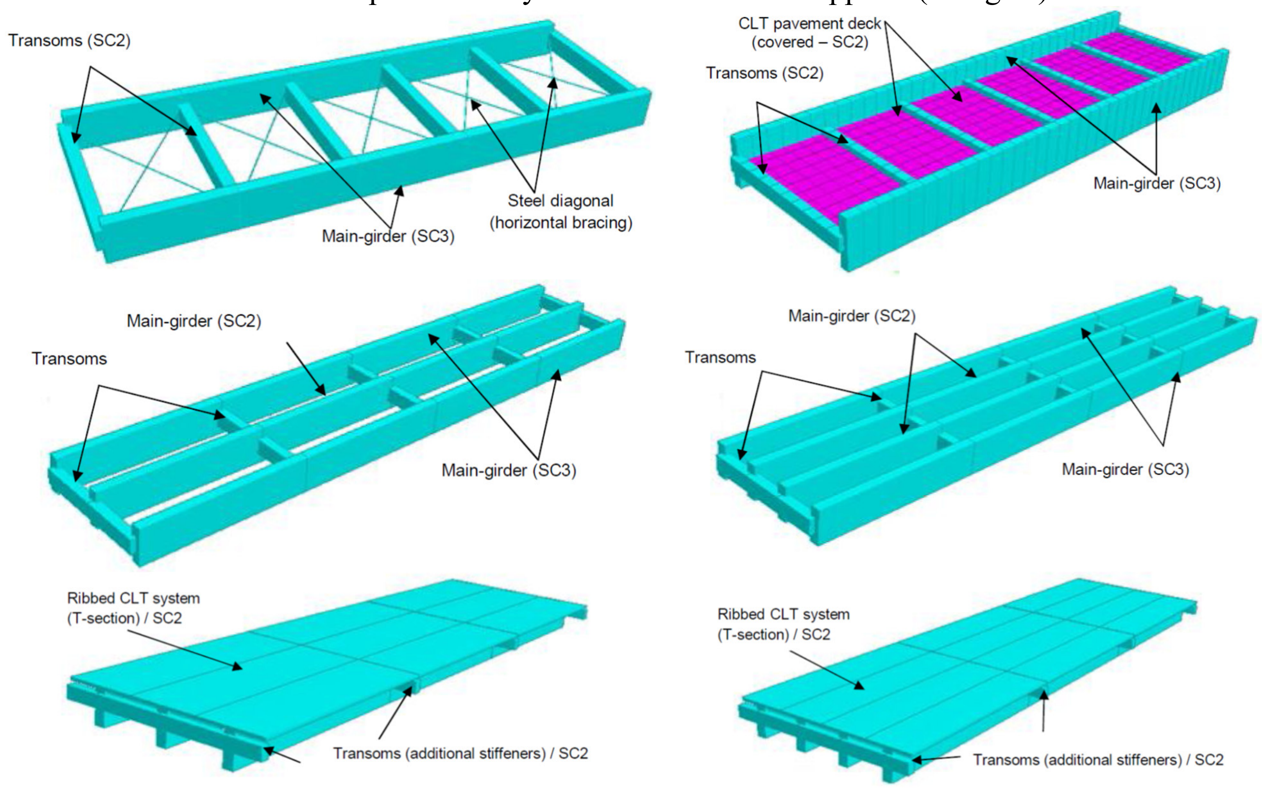


Figure 4. Examples of prepared FE 3D models, as given in Table 2: a) group I.; b) group II.; c) and d) group / subgroup III.; e) and f) group / subgroup IV [1]

2.4 Results of performed static and dynamic analyses. The following limitations of deflections for structural members with its span (*L*) were presumed: *L*/250, for the final, and *L*/300 for the instantaneous deflections, including those caused by pedestrian and cyclist traffic (any their combining with snow load were excluded), and where occasional light traffic (by e.g. emergency vehicle) was treated as an independent load [3]. Dynamic analysis was performed using minimal required dimensions of the structural members resulted from implementation of deflection criteria. Calculated vertical vibrations were within range 2,5 – 4,5 Hz for 1st and 2nd mod of oscillation (the values decrease with increasing the span), while acceleration maxima for individuals or persons in crowds didn't exceed 0,7 m/s^2. In accordance to HRN EN 1990/A2 and [2], both confirms deflections as more important criteria for all studied cases.

3. Discussion of Criterion of Optimisation and Conclusion. Effects of initial criteria for validating optimality of design solution with respect to the span could be discussed by assessing the following detected differences: a) among total quantities of used material when structural members are made of timber of different quality (i.e. when the effect of usage of standard or high strength classes for the same design solution are compared), as shown on Figure 5, and b) between required minimal depths of main-beams, as indicated on Figure 6.

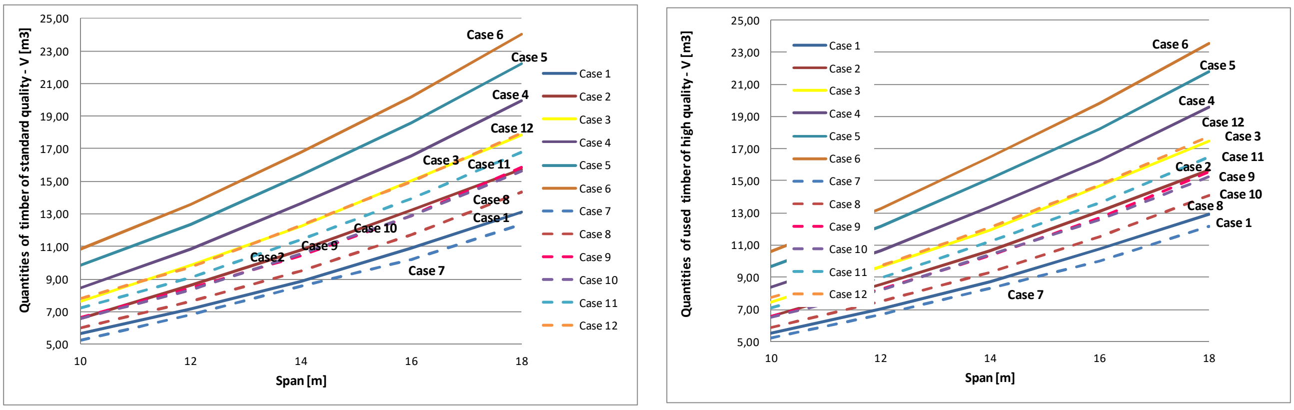


Figure 5. Quantity criterion – the effects of using different strength classes for main-beams [1]

Criterion a) did not prove as extremely crucial because the differences in the consumed material are less than 5%. However, even so little difference may be relevant when more thoroughly analysing the total costs, considering those relating to protection measures, discussed earlier. Also this criterion might be significant for more pronounced differences between qualities of applied materials, when its greater effect on decreasing of dimension is expected.

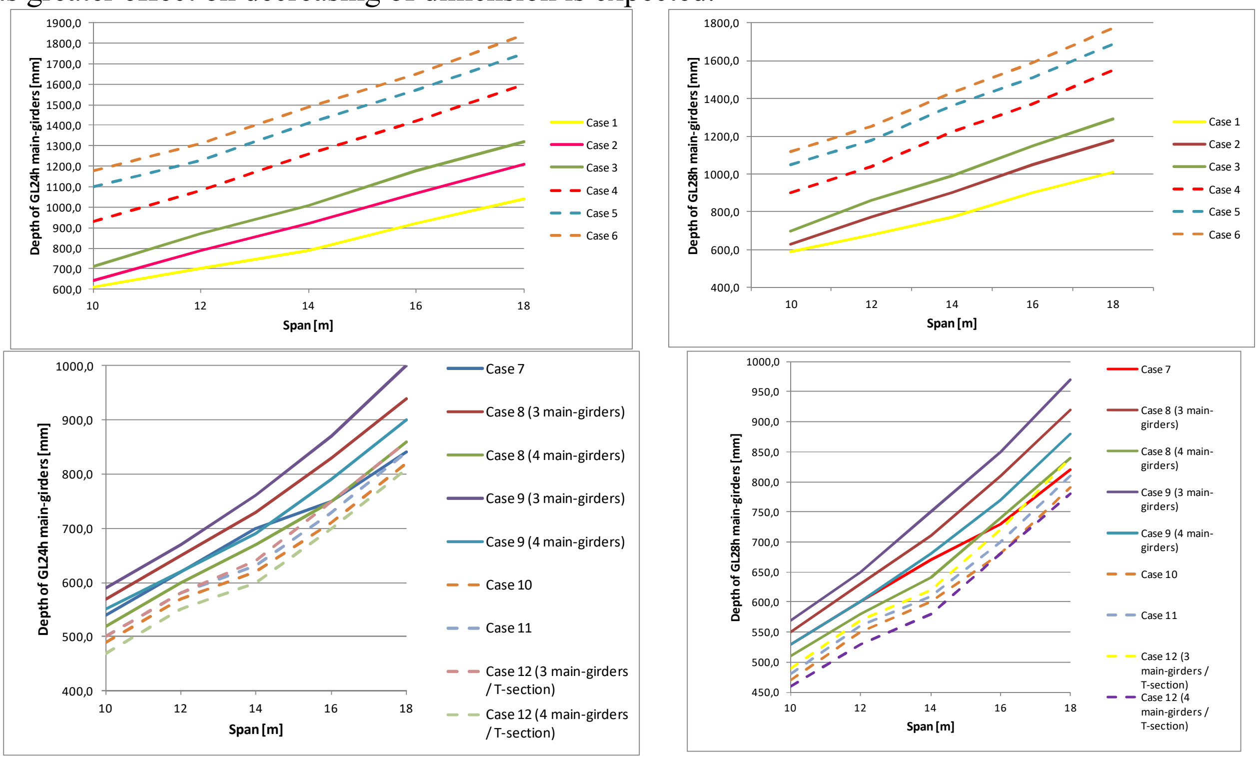


Figure 6. Criterion of required depth of glulam main-beams – the effects of using strength classes of standard (left) and high quality (right) [1]

From the Figure 5, it can be inferred the following: by comparing solutions with CLT deck, grillage systems (Cases 10–12) are more efficient, even when they apply for wider traffic profile. Among comparable cases with planked deck, its upper position is more favourable, although Cases 1 and 7, with the smallest deck width, represent an exception. As can be seen on Figure 6, when criterion of minimum required depth of the main-beams applies, the differences between results of analyses performed for representative strength classes of standard and high quality are less than 10%. It confirms this criterion as more efficient than previous one, but still has not so significant and clear impact on the optimization.

In order to enable easier selection of suitable layout with respect to the span, we introduced an additional criterion - limitation of the main-beams depths, and the results are shown on Figure 7. It ensures better lateral torsion stability of main-beams in all cases with countersunk deck, and also provides more attractive aesthetic appearance to the bridge because remaining height of parapet enables to put the fence and handrails, allowing to users a view. At the other hand, it provides more sufficient clearance beneath the bridge with the upper deck position. Therefore, dimension ratio for rectangular main-beam is limited as 8:1 (i.e. maximal depth of 1,6 m) for Cases 1 – 6, while its maximal depth of 0,7 m is assumed for Cases 7 – 12.

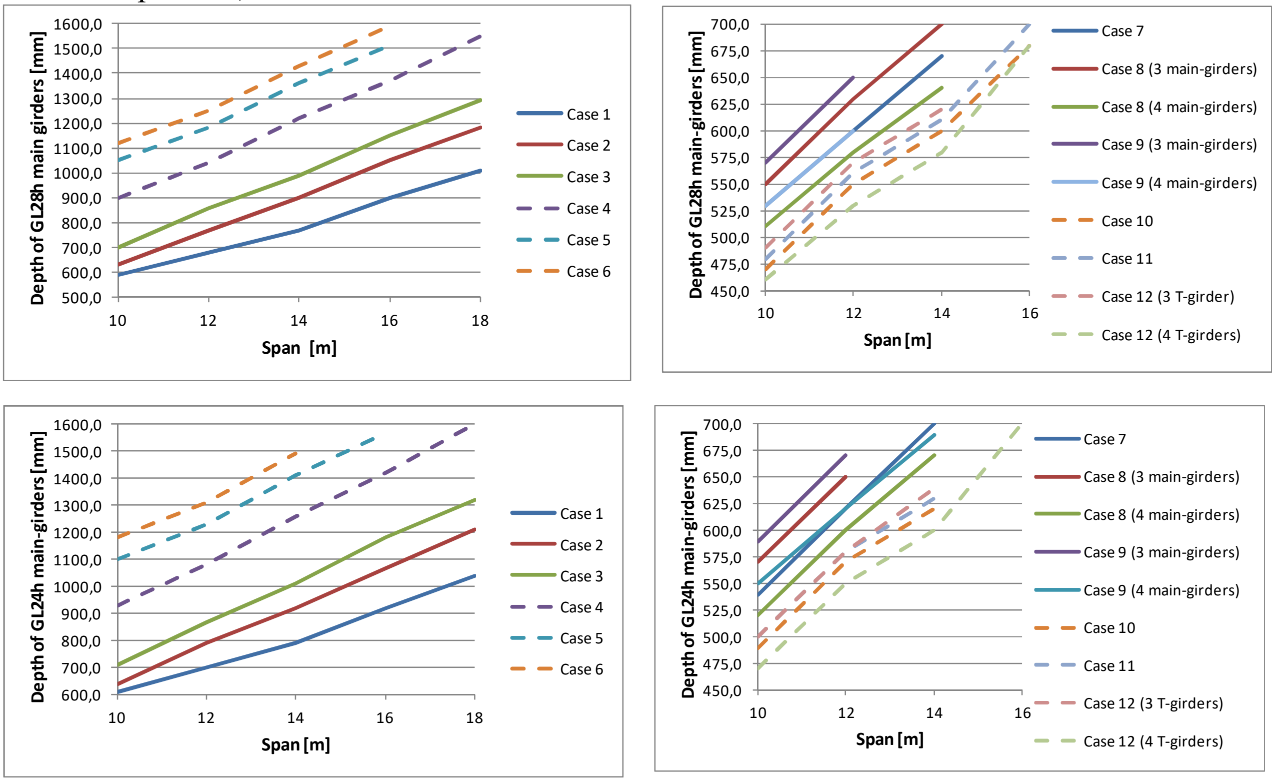


Figure 7. Proposals for optimal layout type with respect to the span of main-beams relating to its strength class and position of the deck: lower position (left) and upper position (right)

The results, compatible with data indicated in Table 1 and Table 2, and collected from the analysis conducted for varied strength classes of main-beams, point to the following:

- For types from I. to III., where its usable widths up to 3,0 m are representative for defined purpose, layout types with sealed plank deck (Cases 1 – 3, group I.) are the most favourable as applicable to all spans.
- For the same types, layout solutions with upper position of planked deck (Cases 7 – 9, group III.) are less favourable respecting the span, and therefore more sensitive to variations of the number of main-beams and strength of used timber, especially for types II. and III.
- Therefore, Case 7, as well as Cases 8 and 9 if they consisting of 4 main –beams can be applied on spans up to 14 m, independently of considered strength class. Layout type with 3 main-beams for usable widths above 2,0 m are suitable only on span up to 12 m, and use of glulam of higher quality (GL28) may be helpful for Case 8 to reach the span of 14 m.
- In general, all types with CLT decks (types IV. – VI. with usable width from 3,5 m to 4,5 m) are able to reach spans of at least 14 m, despite the contribution of their increased self-weight and

permanent load to deflection. It should be noted that usable width of 4,5 m is very comfort and not so common for intended purpose of the bridge.

- For type IV. with lower position of CLT deck (Case 4), the span of 18 m is attainable no matter of applied strength of glulam main-beams.
- For types V. and VI., when the same group II. applies (Cases 5 and 6), the spans of 16 m and 14 m are achievable when main-beams are made of GL24, while the application of GL28 enables larger corresponding spans of 18 m and 16 m.
- For types IV. and V. with grillage system applied (group IV.), the results differ: for Cases 10 and 11 (comparable with Cases 4 and 5), the span of 14 m was reached if glulam ribs of GL24 applied, and of 16 m, where they were made of GL28. The number of ribs didn't produce significant effect on both results.
- For type VI. (Case 12) the same spans are reached for different strength classes of glulam ribs. As it was expected, the number of ribs was the most relevant, where 14 m was maximum for series of 3 T-girders, and 16 m for system with 4 ribs.

All that were noted above stem from the additional criterion we introduced, and its effects are shown on Figure 7. However, for any meaningful rating the optimality of layout type with respect to the span, it is necessary to connect previous observations with the results of application of the initial criterion that is based on the quantities of consumed timber material, as shown on Figures 5 and 6. It should be noted that the results of the analysis are related to the most unfavourable load case – moving load with traced position of emergency vehicle, as shown on Figure 3. According to the above, the following could be recommended for the intended purpose of the bridge:

- When comparable groups I. and II. with countersunk decks apply for the same types of usable traffic profiles, quantities of consumed material are significantly greater when CLT deck is selected instead of the sealed solid timber deck. This is expected and caused by its self-weight and increased permanent load due waterproof layers and asphalt finishing above the deck. For usable traffic widths above 2,0 m, criterion with respect to the span provides an additionally argument to consider design solutions with CLT as less favourable than those with solid timber deck.
- For comparable cases with upper position of the deck (groups III. and IV.), more detailed analyses should be done to recommend more optimal layout type when it is choosing between design solutions with open-boarded deck and those where CLT is used as a flange of composed T-beams in grillage systems. Certainly, more detailed calculation of composed T-section and CLT itself should be performed.
- For the final evaluation of the optimum design solution, the effects of applying the simplest system, with solid timber planked deck should be further analysed in more detail, paying the attention on the influence of pedestrians as dominant load.

And finally, although the goal of the presented research was to develop and evaluate criteria for assessing the optimality of the disposition layout, there are also some its indirect targets which should be highlighted. It promotes timber as a suitable material for bridge structures, but also to point up the benefits of its use: high level of prefabrication and ease of erection. It is very important to include protection strategy early in planning because it enables to discuss levels of protection and types of construction, considering longevity of bridge without major repairs.

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ДЕРЕВ'ЯНІ ПІШОХІДНІ МОСТИ – ВАЛОРИЗАЦІЯ ПАРАМЕТРИЧНОГО АНАЛІЗУ ЩОДО ОПТИМІЗАЦІЇ КОМПОНОВКИ БАЛКОВИХ МОСТІВ

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Анотація. У статті наведено результати аналізу можливих конструктивних рішень дерев'яних балкових мостів з урахуванням усіх звичайних вимог до їх стійкості, міцності, безпеки та функціональності при здійсненні пішохідного та велосипедного руху, а також, за потреби, руху аварійних автомобілів. Параметричні скінченноелементні моделі (ПСМ) мостів з клеєними дерев'яними однопрольотними балками розділено на чотири групи, кожна з яких складається з кількох підгруп. Тип тротуарної плитки (з масиву деревини або настил CLT, покритий шаром асфальту та захищений) та її положення (нижнє чи верхнє) були обрані у якості релевантної характеристики для деякої групи, тоді як тип поперечної компоновки, що відповідає певній ширині настилу та корисному трафіку, а також супутнє рішення просторової стабілізації були визначальними факторами для диференціації розглянутих підгруп. Використовуючи прольоти балок і корисну ширину настилу вимощення, обумовлену вимогами руху як вхідними параметрами, підготовлені ПСМ були розділені на дванадцять різних комбінацій, у тому числі були враховані як статичні, так і динамічні навантаження. За результатами проведеного дослідження розроблені та надані рекомендації щодо вибору оптимальної конструкції, яка враховує фактичну величину прольоту мосту та відповідає вимогам до його функціональності, міцності, стійкості та довговічності.

Ключові слова: дерев'яні балкові мости, велосипедний та пішохідний рух, трафік аварійних транспортних засобів, критерії оптимізації, параметричний аналіз, проектування конструкцій.

ДЕРЕВЯННЫЕ ПЕШЕХОДНЫЕ МОСТЫ – ВАЛОРИЗАЦИЯ ПАРАМЕТРИЧЕСКОГО АНАЛИЗА ПО ОПТИМИЗАЦИИ КОМПОНОВКИ БАЛОЧНЫХ МОСТОВ

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Аннотация. В статье представлены результаты анализа возможных конструктивных решений деревянных балочных мостов с учетом всех традиционных требований к их устойчивости, прочности, безопасности и функциональности при осуществлении пешеходного и велосипедного движения, а также, при необходимости, движения аварийных автомобилей. Параметрические конечнолементные модели (ПКМ) мостов с клееными деревянными однопролетными балками разделены на четыре группы, каждая из которых состоит из нескольких подгрупп. Тип тротуарной плитки (из массива древесины или настил CLT, покрытый слоем асфальта и защищенный) и ее положения (нижнее или верхнее) были выбраны в качестве релевантной характеристики для некоторой группы, в то время как тип поперечной компоновки, соответствующей определенной ширине настила и полезному трафику, а также сопутствующие решения пространственной стабилизации были определяющими факторами для дифференциации рассматриваемых подгрупп. Используя пролеты балок и полезную ширину настила отмостки, обусловленную требованиями движения как входными параметрами, подготовленные ПКМ были разделены на двенадцать различных комбинаций, в том числе учтены как статические, так и динамические нагрузки. По результатам проведенного исследования разработаны и предложены рекомендации по выбору оптимальной конструкции, которая учитывает фактическую величину пролета моста и отвечает требованиям к его функциональности, прочности, стойкости и долговечности.

Ключевые слова: деревянные балочные мосты, велосипедное и пешеходное движение, трафик аварийных транспортных средств, критерии оптимизации, параметрический анализ, проектирование конструкций.