Medium-Span Timber Footbridges - A Comparative Analysis with Traditional Steel and Concrete Structures (Technical, Environmental, and Structural Aspects)

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Case Study within the "Seine – Escaut Est" Project: Structural Adaptations for the 2000-Ton Navigation Standard on the Nimy-Blaton-Péronnes Canal

ANNEX 1: STATE OF ART

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1 STATE OF ART

The following chapter focuses on the analysis of various types of timber bridges**,** constructed across different historical periods. The primary objective is to establish the current state of the art in timber bridge construction, providing a foundation for the analysis and structural evaluations based on a comprehensive historical review.

This section is structured into subsections, each examining specific examples of timber bridges, categorized according to structural typologies, material choices, and static schemes. Furthermore, the analysis considers the span lengths achieved in relation to the selected construction technologies, providing a comparative perspective on engineering advancements and design evolution in timber bridge construction.

1.1 FLISA BRIDGE (Norway)

Figure 1: Flisa Bridge (Norway) - (Flisa Bridge, 2003)

The Flisa Bridge is a Norwegian road bridge, with a total length of 196 meters, making it one of the longest timber road bridges in the world, and a maximum span of 70 meters. The bridge features a hybrid arch-truss structure with diagonal elements: It comprises two support planes and diagonal braces that serve as lateral stability bracing, arranged in an eccentric configuration.

The trusses and parapets are constructed using glued-laminated timber (glulam), while the bridge deck consists of a stress-laminated deck plate made of sawn timber. The new superstructure incorporates nearly 900 m^3 of glued-laminated and sawn timber, which required the use of more than 7,000 trees, along with over 200 tons of steel.

The bridge is built on a foundation of piers from a pre-existing structure, which was already in place. It provides a comprehensive example of a structural solution that integrates timber as a primary load-bearing material, combined with the support of vertical steel tension members (tie rods). This design effectively merges the natural advantages of timber construction with the strength and stability provided by steel elements.

1.2 TYNSET BRIDGE (Norway)

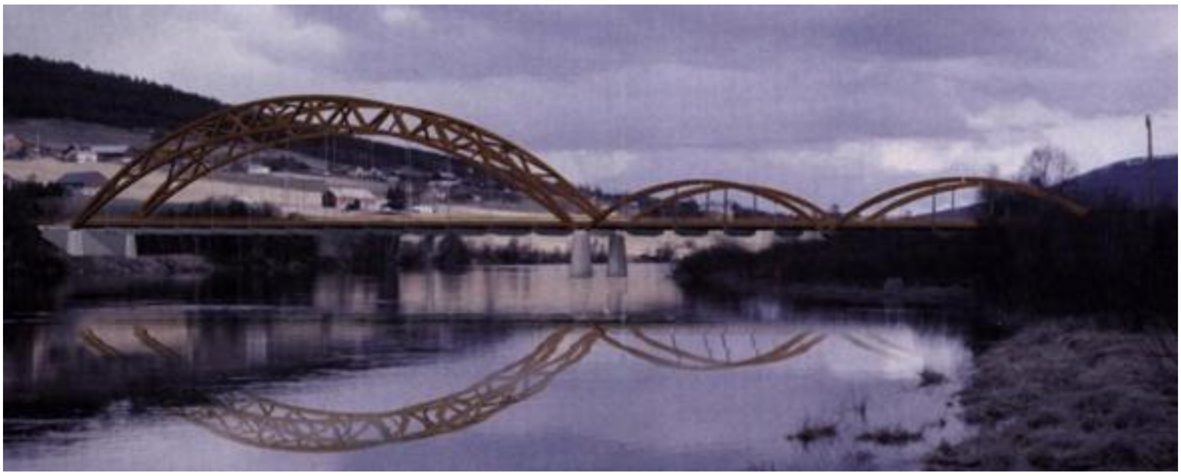

Figure 2: Tynset Bridge (Norway) - (Tyset Bridge, 2000)

The Tynset Bridge is a notable example of a timber bridge, consisting of three spans of varying lengths, specifically 26.5 m, 25.5 m, and 70 m, all supported by a timber arch structure.

A key structural feature of the main arch is its dual-level extrados and intrados, which are interconnected by a truss-like configuration. This design enhances the structural capacity of the bridge, ensuring a more uniform load distribution along the arch. As a result, the structure behaves similarly to a truss system, generating internal compression and tension forces that improve overall stability and load-bearing performance.

The bridge has a total length of 184 m and is a composite structure, incorporating steel tie rods in both vertical and orthogonal configurations to further enhance its structural stability and resistance to dynamic loads.

The structure is composed of glued-laminated timber (glulam), with the bridge deck consisting of a stress-laminated timber plate, which enhances load distribution and durability. The bridge is supported by reinforced concrete piers, providing a stable foundation and additional structural integrity.

1.3 EVENSTAD BRIDGE (Norway)

Figure 3: Evenstad Bridge (Norway) - (Evenstad bridge, 1996)

The Evenstad Bridge is a multi-span bridge with a total length of 180 meters, divided into five spans of 36 meters each. It consists of a sequence of identical repeating arch structures, which are supported by a triangular truss configuration.

The bridge is developed on two support planes, interconnected by eccentrically arranged timber bracings to enhance lateral stability.

The structural arch body is composed of glued-laminated timber (GLT), while steel ties are incorporated to improve structural stability and regularity. Additionally, the bridge deck is made of word, and the piers are made of reinforced concrete, ensuring a robust and durable foundation.

1.4 MISTISSINI BRIDGE (Québec, Canada)

Figure 4: Mistissini Bridge (Québec, Canada) – (Mistissini Bridge, 2014)

The Mistissini Bridge has a total length of 160 meters, consisting of four spans measuring 37, 43, 43, and 37 meters, respectively. It has a width of 9.25 meters, accommodating two bidirectional traffic lanes.

The structural system is composed of semi-continuous glued-laminated timber (GLT) arches, which support GLT beams. More specifically, the bridge integrates arches, slabs, and girders made of glued-laminated timber, while the piers and abutments are constructed from reinforced concrete, ensuring a robust and durable foundation.

From an engineering perspective, this bridge represents a more advanced design compared to previously analyzed structures. Not only is it a more recent construction, but it also features a different structural composition and functional approach compared to the traditional arch-truss systems previously examined.

Additionally, the bridge incorporates a waterproof deck system, which includes a bituminous coating, multiple membrane layers, and marine-grade plywood, effectively protecting the timber elements from environmental exposure and enhancing its longevity.

1.5 NORSENGA BRIDGE (Norway)

Figure 5: Norsenga Bridge (Norway) – (Norsenga Bridge, 2021)

The Norsenga Bridge has a total length of 94.5 meters, accommodating two traffic lanes, along with a dedicated pedestrian and cycling path.

The structure is divided into three lower spans, separated by reinforced concrete piers, which provide a stable foundation for the structural timber load-bearing elements. These elements, characterized by a triangular geometry, support the deck structure resting on top.

The superstructure, composed of two distinct planes, simulates the behavior of an arch, but is clearly segmented by truss elements, which are interconnected by steel components. The bridge features vertical steel support elements but lacks upper bracings connecting the two structural planes. Consequently, the stability of the structure relies on the deck, which is supported by horizontal steel beams.

In general, it can be concluded that the primary structure comprises glued-laminated timber (glulam), with approximately 710 cubic meters utilized in its construction. The bridge's total weight exceeds 400 tons, distributed between both wood and steel components. The construction required 66 tons of black steel and 70 tons of Duplex stainless steel. The transverse carriers, numbering five in black steel and four in Duplex, each weigh between 6 to 10 tons. Additionally, four Duplex hanging pillars, each weighing 2.7 tons, were produced to enhance structural integrity.[1]

[1] (Norsenga Bridge, 2021)

1.6 GANGBRU LEVERT TIL FÅVANG (Norway)

Figure 6: Gangbru Levert Til Fåvang (Norway) - (Gangbru levert til Fåvang, 2022)

The Fåvang Pedestrian Bridge is a single-span pedestrian bridge with a total length of 23 meters and a width of 3.2 meters. It is designed to support a total load of 10 tons, accounting for snow loads and service vehicles, ensuring long-term durability of the structure.

The load-bearing structure consists of pre-stressed toothed glulam beams, which are also fire-treated to enhance fire resistance. This structural solution provides a high load-bearing capacity while maintaining an overall reduced weight. Additionally, pre-compression technology significantly improves the load resistance capacity, enhancing the structural performance of the bridge.

The decking system is made of impregnated pine, which ensures resistance to climatic variations and prevents structural degradation over time.

The lateral stability of the bridge is highly controlled through the integration of wooden bracing systems. Furthermore, the use of pre-stressing technology effectively reduces beam deflection and vibrations, thereby enhancing the stability and comfort of pedestrian movement on the bridge.

1.7 CUBILLAS FOOT BRIDGE (Ramales de la Victoria – Cantabria)

Figure 7: Cubillas Foot Bridge (Cantabria) - (El puente de madera más largo sobre los ríos de Cantabria., 2023)

The Cubillas Footbridge is a timber pedestrian bridge with a total length of 46 meters, featuring a single-span structure and a width of 2.5 meters.

The primary structural system consists of two laminated timber beams, which are suspended and supported by two levels of overhead arches, facilitating seamless integration with the surrounding environment.

Notably, the underside of the deck houses purification conduits for the Asón River, actively contributing to the sanitation and environmental preservation of the surrounding area.

The structural body is composed of glue-laminated timber (glulam), with steel elements used to stabilize the connections, while the foundations are made of reinforced concrete.

The bridge was constructed using a prefabrication method, where the structure was assembled off-site and later positioned in place using cranes[2]. This construction technique was likely feasible due to the relatively short span length and the structural stability of the bridge body.

Additionally, bracing elements are present between the two planes of the structural arches, enhancing the overall stability and load distribution of the bridge.

[2] (Montaje del puente de madera en el río Asón, Ramales de la Victoria, 2022)

1.8 BETANZOS WOODEN FOOTBRIDGE (Río Mandeo en Betanzos – Galicia)

Figure 8: Betanzos Wooden Footbridge (Galicia) - (Betanzos - El nuevo puente de madera sobre el río Mandeo se instalará el próximo jueves, 2011)

The Betanzos Wooden Footbridge is a pedestrian bridge originally constructed in 1992 and later replaced with a new structure in 2011. The bridge features a single-span design with a total length of 40 meters and a width of 2.5 meters.

Its primary structural components are made of glued-laminated timber (glulam) to provide a balance between structural stability and aesthetic integration. The bridge is designed as a double-plane arch structure, where the wooden deck is connected to the arch by vertical timber elements, ensuring a cohesive and lightweight structural system.

The bridge was prefabricated off-site and subsequently transported and installed using cranes, minimizing construction time and on-site labor efforts[3].

The foundations, constructed from reinforced concrete, are designed with specific geometry and depth to address the challenging soil conditions, characterized by high clay content up to a depth of 11 meters. This geotechnical challenge is partially mitigated by the lightweight nature of the glulam structure, reducing the load impact on the foundation system.

[3] (Montaje del Puente de Madera sobre el Río Mandeo en Betanzos, 2011)

1.9 CASTOR RIVER WOODEN FOOTBRIDGE (Estepona, Málaga, Spain)

Figure 9: Castor River Footbridge (Estepona) - (El Puente sobre el río Castor parte desde nuestras instalaciones, 2023)

The Castor Footbridge is a pedestrian bridge that is part of the Senda Litoral Plan, a program aimed at integrating the territorial and environmental diversity of the province into a single route, creating a meeting point between various cultural and environmental aspects.

The bridge has a total length of 32 meters, featuring a single-span structure with a width of 3 meters.

The primary structural system consists of a slightly curved truss beam, made of Nordic wood (Scots pine), composed of chords, verticals, and diagonals of glued-laminated timber (GL28h strength class).

During construction, the bridge was prefabricated off-site and later transported to its final location, to minimize construction costs and ensure a high level of quality control[4].

[4] (Montaje del Puente de Madera sobre el Río Castor en Estepona, 2023)

1.10 ANILLO VERDE FOOTBRIDGE (Vitoria-Gasteiz, Spain)

Figure 10: Anillo Verde Footbridge (Vittoria-Gasteiz) - (Puente de 61 m x 3 m Anillo Verde, en Vitoria-Gasteiz (4469), 2022)

The Anillo Verde Bridge has a total length of 61.08 meters and an effective width of 3 meters. This single-span structure crosses over the N-102 highway, connecting the Zabalgana neighborhood with the Armentia natural forest, thereby integrating into the city's 31-kilometer Green Belt.

The bridge features a three-hinged arch structure, allowing the entire arch to be fully prefabricated. This design enables the construction and transportation of the bridge in two separate modules, which can be easily lifted and assembled on-site using cranes.

The bridge incorporates a lowered arch, which transmits forces parallel to the intrados, while the deck is positioned above the extrados. This structural configuration enhances efficiency, avoiding the need for excessive elevation at the crown, while maintaining suitable slopes for cyclists and individuals with reduced mobility.

1.11 PASSERELLE MANGIN (La Rochelle, France)

Figure 11: Passarelle Mangin (La Rochelle) - (La Rochelle : et voici la fameuse passerelle Mangin, 2021)

The Passerelle Mangin is a pedestrian bridge measuring 40 meters of length and 3 meters of width, structurally composed of two arch support planes, which are slightly inclined towards the static centroid of the structure and interconnected by horizontal elements, also made of timber, to enhance overall stability.

The bridge features a gently curved structure, where timber is combined with steel to provide increased structural strength and stability. In this specific case, the construction was carried out directly on-site, ensuring precise assembly and integration with the surrounding environment.

1.12 AUBE FOOTBRDIGE (Troyes, France)

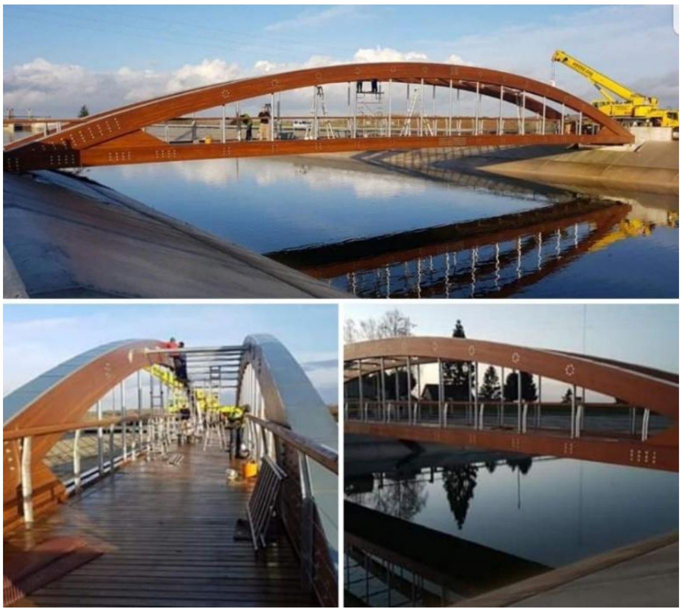

Figure 12: Aube Footbridge (France) - (Puente 50x3 Aube (Francia), 2023)

The Aube Bridge is a pedestrian bridge with a total single-span length of 50 meters and an effective width of 3 meters. It is structurally designed as a timber arch bridge, where two glulam arch planes function as the primary load-bearing elements.

The bridge features two arches spanning the full length of the structure, ensuring efficient load transfer and structural stability. Steel vertical hangers connect the deck to the arches, providing optimal load distribution and reinforcement. The deck is composed of timber planks, offering both durability and aesthetic integration with the environment. Additionally, steel railings enhance safety and user comfort, while maintaining a lightweight yet robust design.

During construction, the bridge was prefabricated off-site and subsequently assembled in place, utilizing cranes to position the structural elements efficiently. This method optimized construction time and ensured high precision in the installation process.

1.13 ARROYO GUADALOBÓN FOOTBRIDGE (Estepona)

Figure 13: Arroyo Guadalobón (Estepona) - (Puente 42x3 - Arroyo Guadalobón (Estepona), 2023)

The Arroyo Guadalobón Bridge is a pedestrian timber bridge featuring a double-plane structural arch with a single-span configuration. The bridge has a total length of 42 meters and a width of 3 meters.

The arches are constructed from glued-laminated timber (GLT), and the bridge's distinctive structural characteristic lies in its entirely timber-based composition. Not only are the arches made of timber, but also the vertical elements, the deck, and the horizontal components that interconnect the two structural arch planes, creating a fully wooden structure.

The entire system is stabilized and reinforced through steel connections, ensuring structural integrity and rigidity.

The walking surface consists of timber planks, which provide a natural aesthetic while maintaining a sturdy and durable platform for pedestrians.

The bridge was prefabricated off-site, allowing for precise manufacturing and quality control. Subsequently, the prefabricated components were transported to the installation site, where cranes were used to efficiently assemble and position the structure. This construction approach minimized on-site assembly time and reduced environmental impact, optimizing the overall efficiency of the project.

1.14 ARROYO GUI FOOTBRIDGE (Torrox, Málaga)

Figure 14: Arroyo Gui Footbridge (Torrox) - (Una nueva actuación de la Senda Litoral une Torrox con Vélez-Málaga, 2021)

The Arroyo Gui Bridge is a timber pedestrian bridge with a single-span configuration of 30 meters. It is designed as a segmented arch bridge, where individual segments are connected by vertical elements, which function as vertical stabilizers. Despite its arched shape, structural behavior is more akin to a truss bridge due to the segmentation and load distribution.

All structural components are made of glued-laminated timber (glulam), including the two primary arches, which support a timber deck. The connections are secured using metal plates and bolts, ensuring structural integrity and stability.

The bridge was prefabricated off-site, allowing for precise manufacturing and quality control. Subsequently, it was transported and installed on-site using cranes, ensuring efficient assembly and integration into the surrounding environment.

1.15 GUADALHORCE BRIDGE (Malaga)

Figure 15: Guadalhorce Bridge (Malaga) - (Puente de madera con 273 m sobre el río Guadalhorce, Málaga (5082), 2022)

The Guadalhorce River Footbridge in Málaga is a pedestrian bridge with a total length of 273 meters and a useful width of 3 meters. The bridge is composed of seven spans arranged in a symmetrical configuration with increasing lengths. The central span, which crosses the main branch of the Guadalhorce River, measures 69.66 meters, making it the longest span. The adjacent spans are 55 meters, followed by spans of 31 meters and 15 meters, respectively.

The bridge employs a multi-arch structural system, where several arches work in unison. This design necessitates meticulous adherence to geometric precision during construction to achieve static equilibrium. Initially, the proposed geometry positioned the arches nearly at ground level. However, hydrological studies revealed that, during a 500-year return period flood event, a significant portion of the structure would be submerged. Consequently, the final design reduced the curvature of the arches, ensuring that the entire superstructure remains above the Q500 flood line, at 7.1 meters above sea level[5].

The bridge's design is influenced by its ecologically sensitive location, leading to the selection of glued-laminated timber (glulam) as the primary construction material. The use of glulam allows for economically effective spans ranging from 30 to 70 meters, thereby minimizing the number of supports needed and reducing the environmental impact on the protected natural area.

[5] (Puente de 273m sobre el Río Guadalhorce, Málaga, 2022)

1.16 PEÑAFIEL BRIDGE (Valladolid)

Figure 16: Puente Peñafiel (Valladolid) - (Montaje del Puente de Peñafiel, 2022)

The Peñafiel Bridge is a pedestrian timber bridge, with a total length of 50 meters and a useful width of 2 meters, featuring a dual-level arch support structure. The two lateral glulam arches are inclined towards the structural centroid to enhance stability; however, these two planes do not directly connect and are instead linked by horizontal timber elements.

The arches support a timber deck, which rests on two lateral glulam beams, while horizontal base elements act as bracings, ensuring deck stability and load distribution.

The entire structure is constructed using glued-laminated timber (GLT), with steel plate and bolt connections securing the joints.

The construction process was fully managed off-site, with the bridge being prefabricated and subsequently installed on-site using cranes, optimizing precision, efficiency, and minimizing environmental impact.

1.17 RIVER CALORE BRIDGE (Benevento, Italia)

Figure 17: River Calore Bridge (Benevento) - (Ponte ciclabile sul fiume Calore - Benevento, 2005)

The River Calore Bridge in Benevento (IT) is a pedestrian and cycle bridge with a total length of 115 meters and a maximum clear span of 70 meters.

The bridge exhibits a clear division into two distinct structural technologies. The lateral sections function as a cable-stay bridge, featuring steel pylons and cables anchored to reinforced concrete piers.

The central section, however, acts as an inverted arch, simply supported at both ends by the cable-stayed structure. This arch section consists of two parallel glued-laminated timber (GLT) planes, which are connected to the GLT deck via vertical steel elements.

The two GLT planes are further stabilized by steel bracings, arranged in a cross-bracing configuration, and horizontal timber elements, ensuring lateral stability and structural integrity. The connection between the central and lateral sections establishes a structural behavior akin to a simply supported system.

Additionally, the deck features a pre-curvature, which likely reduces deflection and enhances load-bearing efficiency under various loading conditions.

It is important to note that the bridge is designed for cycling traffic and was constructed entirely using prefabricated methods. The central section was prefabricated off-site and later installed on-site, seamlessly integrating with the rest of the structure using specialized cranes.

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