



Bridges Built with Advanced Materials

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ABSTRACT

In spite of the impact that composite materials and Stainless Steel have had in the aircraft and naval construction industries, architecture or multitude of consumer products for more than 50 years, their presence in civil engineering structures is recent. In the last two decades some interesting structures, mainly pedestrian bridges, have been built. Advanced materials such as Stainless Steel and GFRP (Glass Fiber Reinforced Polymers) make possible to build light, durable, safe, and elegant structures. The higher construction cost is offset during the life of the structure thanks to the minimum maintenance required for these materials. This paper provides an overview of the design criteria; performance, unique properties and applications of these advanced materials in bridges through several case studies designed by the authors and built in Spain in the past decade.

1. ADVANCED MATERIALS FOR BRIDGES

There is a need of advanced structural materials for applications in aggressive environments or for reducing weight. The use of advanced materials allows to building light, durable and attractive bridges. Stainless steel (typically Duplex Grades) and GFRP (Glass Fibre Reinforced Polymers) are high durable materials that provide outstanding mechanical properties and magnificent aesthetical possibilities (Baddoo et al., 2012), (Keller, 2003). The larger construction cost can be offset during the long life of the structure thanks to substantial savings in the cost of maintenance and replacement of bridge components.

The full potential of these two materials is reached in locations with aggressive environment (for instance in marine environments or where de-icing salts are used) and their application is steadily increasing.

1.1. Duplex Stainless Steel

Though the variety of the stainless steels is enormous, it is possible to find more than 100 types of frequently used grades, they contain as a common denominator the presence of at least 11 % of chromium that, with the presence of other components as nickel, molybdenum or nitrogen, among others, gives a steel alloy that exhibits a great corrosion resistance, ductility and mechanical strength, even when exposed to high temperatures, as well as excellent aesthetic possibilities and easy maintenance and cleaning. The chromium contained in the stainless steel forms a soft, stable and transparent layer of chromium oxide (Cr_2O_3) on the surface (passivation layer) that avoids corrosion.

Four types of stainless steel exist according to their metallurgical structure: ferritic, austenitic, duplex and martensitic. Duplex stainless steel is an austenitic-ferritic alloy with a microstructure of great corrosion resistance, excellent ductility and mechanical characteristics superior to the great majority of carbon steels. Thanks to their high

strength, duplex steels are suitable for application in bridges and pedestrian bridges (Baddoo, 2013) (Helzel, 2004). With the existence of a wide range of duplex steel grades, the selection of the most suitable type clearly depends on the ambient aggressiveness, type of corrosion, mechanical properties, types of surface finish, and so forth.

Stainless steel, unlike the conventional carbon steels, presents a mechanical nonlinear behaviour, even under reduced stress values, without having an elastic limit strength clearly defined. However, the stress value associated to a strain of 0.2% has been adopted as a conventional yield stress $f_{0.2}$ (Baddoo, 2013). Processes of construction with stainless steel are similar to those used for carbon steels but not identical, adopting specific techniques for cutting, bending, forming, welding, and finishing. Welding consumables must also be specific to the stainless steel grade to guarantee equal mechanical and corrosion properties to those of the base material.

1.2. Glass Fiber Reinforced Polymers (GFRP)

FRP materials are frequently used in aerospace, marine, automobile and leisure industries when high mechanical strength, light weight and corrosion resistance are needed. Glass Fiber Reinforced Polymers are composite materials made of Glass fibers (long or short fibers) on a polymeric matrix (usually isophthalic polyester, vinylester, epoxy or phenol). Typically, the matrix has low strength and modulus of elasticity with high ductility and fibers (the reinforcement) provide high mechanical properties to the composite material although they exhibit a brittle behaviour. The arrangement of the fibers may be random or with a preferred orientation. The mechanical and chemical properties of the material depend on the properties, arrangement and proportions of the constituents and are strongly influenced by the fabrication process (Keller, 2003) (ASCE, 2011).

The use of fibre-reinforced plastic profiles in civil engineering structures has undergone a significant development during the 90's. From the construction of the cable-stayed footbridge at Aberfeldy - UK, 1992- to that of the Pontresina footbridge -Switzerland, 1997-, several hundred further bridges have been built in the past twenty years (mostly pedestrian bridges). Most of these recent structures are truss-type bridges using GFRP pultruded profiles.

Pultrusion is a fabrication process to produce composite profiles with constant cross-sections and mechanical properties. Typically, GFRP pultruded profiles have modulus of elasticity ranging from 23 to 28 GPa and flexural strength around 240 MPa in the longitudinal direction. The density of the GFRP is usually 1.8 (ASCE, 2011).

GFRP exhibits excellent mechanical properties and light weight but due to its relatively low modulus of elasticity GFRP structures are flexible and sensitive to dynamic effects. Combination of GFRP and steel provides stiff structures and still a reduced weight as has been proven in recent structures included in this article.

2. CASE STUDIES

2.1. Minorca stainless steel vehicular bridge

This is the world's first duplex stainless steel vehicular bridge. The bridge, built in 2005, crosses the Algendar River in Cala Galdana (Minorca, Spain) and replaced an existing reinforced concrete bridge that experienced a significant deterioration after 30 years of exposure to a marine environment. After 9 years of service, the new bridge is in excellent conditions and has not undergone any corrosion.

During the design process, different structural and material alternatives were analysed. Finally, a duplex stainless steel arch structure was chosen due to its high resistance to corrosion from the marine atmosphere, as the solution that better responded to the owner's requirements. The new bridge has become a landmark for the island, thanks to the technological innovation of using stainless steel.

The overall length of the bridge is 55 m with a 13 m wide deck. The deck allocates 2 lanes of road traffic (7 m) and two lateral sidewalks, each 2 m wide that allow the pedestrians to enjoy the panoramic views from an excellent location (Figure 1). The main structure consists of two parallel arches with an intermediate deck. The arches and the deck join at the abutments by means of an inclined strut that takes the horizontal component of the arch axial force and, consequently, significant horizontal forces are not transferred to the abutments.



Figure 1. Minorca Duplex Stainless Steel Bridge.

The structural scheme is constituted by two parallel arches with a free span of 45 m and an intermediate deck. The main structure is made of duplex stainless steel grade 1.4462, which exhibits a high resistance to corrosion by chlorides. The deck is made of reinforced concrete connected to a series of transverse beams. The arches rise to a total of 6 m (relation span/rise = 7.5) and they are tied to the deck by means of two connected longitudinal beams. These longitudinal beams are again connected by means of transverse beams. The arches have a triangular cross-section with a central web. Their depth is 0.70 m - constant throughout their overall length. However, the width of the section varies between 0.7 and 1 m. The central web of the section is transformed into a cellular plate that allows connecting the arch with the longitudinal deck beam. The longitudinal beams are rectangular hollow sections of 1 m x 0.5 m, constituted by plates with varying thicknesses between 15 and 25 mm. In the central zone with the arch above the deck, these beams have a central web that is connected to the web of the arch, allowing direct transfer of the vertical loads of the longitudinal beam to the arch. The transverse beams, spaced at 2m, are formed by rectangular cross-sections 0.25 m wide and with a variable depth varying between 0.50 and 0.57 m (to obtain) the deck cross-slope of 2%), constituted by plates of 10 and 12 mm. These beams are structurally connected to the reinforced concrete slab, having an average thickness of 0.30 m, by means of Bernold type studs of 20 mm in diameter.

In order not to transmit the horizontal component of the arch axial force to the abutments, two inclined struts – connecting the base of the arch and the end of the longitudinal beam have been designed, which are anchored at the top of the abutments. The struts have a rectangular hollow cross-section, with outer dimensions of 1 m x 0.5 m, formed by plates of 20 and 25 mm thickness, internally stiffened in both longitudinal and transverse directions.

The lateral sidewalks are separated from the road by the arches. These sidewalks are supported by means of a reinforced concrete slab supported on transverse cantilever ribs every 2 m connected to the longitudinal beam.

2.2. Sant Fruitós Pedestrian bridge

Sant Fruitós is a small town with more than ten centuries of history. Located 59km from Barcelona, close to Manresa, it occupies a strategic position for road communications in Catalonia. The 20th century economic boost and population growth have led to the creation of new residential areas around the historic core, and consequently of new public infrastructures. The neighbourhood of Rosaleda, a new residential area of Sant Fruitós which hosts more than 6% of its population is separated from a commercial district and the rest of the town by the N-141C, a national road. The crossing of this road has caused many accidents, some of them with casualties, on the last few years. The Municipality decided to eliminate this risk by building a pedestrian bridge. Additionally to its main function, the structure should be a new landmark and a gateway to the town, representing its dynamic and innovative nature.

The location of the bridge was fixed by the owner to provide a direct access to a bus stop. The bridge, built in 2009, crosses the N-141C road with a vertical clearance of 5.5m connecting areas with almost a difference of 6m in elevation (Figure 2).



Figure 2. Sant Fruitos pedestrian bridge.

The use of a bow-string reinterpretation - a classical structure as main element - and the stainless steel and GFRP (glass fibre reinforced polymer) – high-performance and structurally innovative materials – are the key concepts. The leaned arch creates a dynamic and tense feeling, and joins the deck for greater structural efficiency. The structure is sober, very transparent and simple, yet very expressive thanks to the use of extremely slender elements and the arch geometry. The crossing is now accessible to disabled people and bicycles, by the slender concrete stairs and panoramic lift on the residential side, and the embankment stairs/ramps and stairs on the other.

The structure, with an overall length of 55 m, is a tied arch with an intermediate deck. The main components are made of duplex stainless-steel. The 40m span arch has a triangular section, almost equilateral, only 0.45m high, and it is tilted in plan and elevation, forming an angle of 30 degrees with the vertical plan. The arch cross-section is fabricated with 20mm steel plates. The 3m wide deck consists of a longitudinal trapezoidal box girder with ribs. The box cross-section is made of 10mm thickness plates. Its shape is almost triangular, 1.60m wide, with constant depth of 0.6 m. The webs are 0.15 and 0.60m in height. The 1.40m long ribs have a variable depth between 0.09 and 0.15m. The deck is connected to the arch at one of the ends (elevator side) and in one intermediate section (36 m from the elevator side). Stainless steel bars hangers, 28mm in diameter, spaced every 3m, connect the deck and the arch.

The arch is supported in the elevator structure and on the other side rest over a small pier. To not transmit any horizontal force to the pier's foundation, an inclined strut element connects the end of the arch, 5 m below the deck level, to the deck creating a V shape below the deck. The light arch and the deck connected through hangers define one of the most characteristic features of the structure, a very attractive visual lightness and slenderness.

The 1.4162 duplex stainless steel used in this footbridge contains less nickel than other duplex stainless types. Therefore, its price is less variable and much lower than other duplex steels. It is suitable for environments with an average level of aggressiveness and it has a conventional yield strength of 480 MPa (more than 35% those of S355 carbon steel).

The deck consists of GFRP panels 0.5m wide 40mm in depth simply supported on the ribs or on the box girder. To avoid sliding, these panels have a quartz sand surface coating.

The dynamic test was conducted with people walking, running or jumping (1 to 9 people) including eccentric load cases. 21 different load cases were defined covering a wide range of probable situations. The response of the bridge to dynamic load met the regulations, and was very similar to the results of the dynamic calculation. Measured critical damping ratio is 0.0127.

2.3. Lleida Pedestrian bridge over the High Speed Rail

This pedestrian bridge, shown in Figure 3, is located 3 km from the city of Lleida (Spain), and was built in 2001 to cross an already existing roadway, a railway line and the new projected high-speed rail-way line between Madrid and Barcelona. The owners required a new pedestrian structure with minimum maintenance and which would be easy to erect. At the time of construction, it was the first arch made of GFRP and the longest span made of standard GFRP pultruded profiles. After 12 years of service, the bridge is in excellent condition and has not required any maintenance.

The most significant issue was that of finding an appropriate structural form to span the required 38 m of length using standard GFRP profiles. The final structure is a double-tied arch of 38 m span-length having a rise of 6.2 m (span/rise \approx 6) and 3 m wide. The total weight of the bridge is approximately 19 Tons (Figure 3).



Figure 3. Lleida GFRP pedestrian bridge.

All the profiles are made of fibre-reinforced plastics using continuous E-glass fibres combined with woven and complex mats having a minimum glass-fibre content of 50 %. The matrix is made of isophthalic polyester. The modulus of elasticity in the longitudinal direction ranges from 23-27 GPa, depending on the type of profile. Its tensile or compressive strength in the longitudinal direction is 240 MPa and its strength in the transverse direction varies from 50-70 MPa.

The arch configuration was chosen so as to minimize serviceability problems due to the low modulus of elasticity of GFRP profiles. The arches have been inclined by 6° to achieve a more expressive appearance. Both arches and the tied longitudinal members present a rectangular hollow cross-section made up of two U 300x90x15mm profiles joined with glued flat plates of 180x12 mm so as to form a hollow rectangular tube. The supplier of the profiles carried out full-scale testing to verify the beam joints using the proposed epoxy adhesive. In order to reduce horizontal deformation of the arches due to wind pressure, these elements are forked out into two branches using the same profiled sections.

The hangers are I-profiles of 160 x 80 x 8. The arches are connected by square tubes of 100 mm size and having various thicknesses (6-8 mm). The deck is made up of transverse I-beams of 200x100x10 mm, spaced at 0.6 m from one another and they directly support the 4 cm thick deck panels that form the transit or roadway surface. A bracing system, to avoid distortion, was designed using diagonal U-section members of 160x48x8 mm as a typical cross-section.

All the above-mentioned structural elements are made of pultruded glass-fibre composite materials which were manufactured in Denmark and transported to Spain to be assembled here. The maximum length of the elements transported is 9 m. The chief problem with GFRP structures is the design, construction and assembly of the joints due to the anisotropic behaviour of the profiled members. As a result of the lack of experience with glued connections on bridges, all joints are bolted using stainless steel brackets and bolts. Diagonal elements were added in the design, joining the nodes of the arches and the tied longitudinal members, to improve the dynamic behaviour of the bridge. To reduce its visual image, stainless steel cable elements of 12 mm in diameter were selected.

Access to the arch bridge is designed with reinforced concrete ramps conceived as a continuous beam of 10 m maximum span-length and 0.6 m in depth. The slope of the ramps is limited to 8% so as to guarantee complete accessibility to disabled persons.

2.4. Zumaia Pedestrian bridge

This pedestrian bridge is the first hybrid structure made up of Stainless-Steel and GFRP. The bridge is located in Zumaia, a small town of Guipuzkoa (Basque Country, Spain). In 2007 we were awarded to put forward the design of a pedestrian bridge over Narrondo River connecting a public school and some sport facilities on the other side of the river.

The idea was to design a bridge that enhances the natural value of the River, understanding its environment instead of creating a useless or spectacular landmark bridge. The proposal is a pure and sober structure, but with an innovating and challenging spirit. As the pedestrian bridge is located in a corrosive environment due to its proximity to the sea (less than 400 m), the selection of materials with high corrosion resistance has been crucial.

The pedestrian bridge at Zumaia is the first bridge in combining two high performance materials: stainless steel (grade 1.4462) and composites (GFRP) in composite action. The bridge crosses a 28 m long channel with a 5 m wide deck. The structural outline consists of two Vierendeel trusses that function as guardrail in which the lateral lighting and handrail are integrated. A hybrid structure combining duplex stainless steel and was chosen due to its high resistance to corrosion from the marine atmosphere and lightness as the solution that better responded to the owner's requirements (Figure 4).



Figure 4. Zumaia pedestrian bridge.

The deck allocates a 2 m wide bicycle lane and a 3 m wide sidewalk. The structural scheme is constituted by two Vierendeel trusses with the main members in duplex stainless-steel parallel with a free span of 28 m and a suspended 5 m wide deck. The main structure is made of duplex stainless steel grade 1.4462, which exhibits a high resistance to corrosion by chlorides. The deck's design concept is very simple in order to make the construction easier and to reduce the number of profile types. The deck is made of GFRP pultruded panels (40 mm depth) supported on a series of transverse GFRP or Stainless-steel beams, spaced at 1 m. The planks used for the railing and for the pavement are translucent to emphasize the lightness appearance.

Longitudinal top chords consist of a plate of 300x28 mm, the bottom chords have a rectangular cross-section 360 mm wide with variable depth between 300 and 400 mm made of plates 12 mm thickness. Transverse beams, spaced at 1 m, are formed by GFRP I-beams with a 300 mm depth except four of them which are made in stainless-steel. All connections between stainless steel members and GFRP beams or panels are bolted using stainless steel bolts and brackets of the same material. The vertical posts have an open Pi-cross-section made of stainless steel plates. The post integrates the lighting system. The railing is made of banister wood supported on steel plates.

The analysis and design of the bridge has been carried out using the criteria from Eurocode-3, part 1.4, including existing European recommendations. The ultimate limit state (ULS) requirements have been checked in all the structural members of the bridge, such as chords, transverse girders and Vierendeel trusses. The main issue for the ULS verification is the composite collaboration of the GFRP panels and the steel members. The principal objection of using this combination is the lack of ductile behavior of the panels in comparison with the steel ductility. The available information on this issues remains insufficient due to the main researchers are still carried out on other fields. Due to that, the ultimate limit state verification on the trusses has been done without considering the GFRP web panel collaboration.

The collaboration between the trusses and the GFRP panels has been considered for the verification of deflection or vibration Serviceability Limit States. GFRP elements provide a large damping compared to steel (about 2-3% of the critical damping) and this is very beneficial for the dynamic behavior of such light structures.

An intense experimental research was done during the construction of Zumaia Bridge. The main goal of this research is to improve the current knowledge on this innovative material. As we have mentioned previously, there are still uncertainties on the behavior of this material when used on structures.

The tests were focused on determining the ultimate loads of the material under compressive and tensile forces. Furthermore, the connections using adhesive or steel bolts have been analyzed. Figure 5 shows some of the performed tests to evaluate the capacity of the bolted connections. Mechanisms of failure are due to shear-out failure or bearing failure, depending on the load and the distance of the bolt to the edge of the panel. Design manual provided by the GFRP supplier (Fiberline), is an excellent tool for designing the connections and the failure loads predicted with the simplified formula is in good agreement with the failure loads obtained at the experimental test. Panels subjected to axial loads have an elastic behavior and they fail due to buckling instability that can be predicted by the Euler critical load.

The static and dynamic performance was a main concern during the design. Users are highly sensitive to vibrations and finishing details. Both static and dynamic tests were performed, and the obtained structural response was very similar to the predicted one, and met all the reference regulations.



Figure 5. Load test to evaluate the capacity of bolted connections (left) and axial capacity of web panels (right).

2.5. Vilafant Pedestrian bridges

The high speed railway line connecting Barcelona and the French border crosses the Municipality of Vilafant 6 m below the ground level. To cross the sunken railroad, two pedestrian bridges have been planned. The structure, with one span of 46 m, is monolithically connected with the abutments. The use of unusual geometric shapes fabricated using stainless-steel and GFRP are blended in an innovative fashion, giving rise to an austere and elegant solution (Figure 6). The two pedestrian bridges were completed in 2011.



Figure 6. Vilafant pedestrian bridges.

The two bridges have a main longitudinal span of 45.2 m and a width-deck of 4 m. The structures are built-in on both abutments. The cross-section consists of two supported Vierendeel trusses made of duplex stainless steel grade 1.4162 combined with double-sheets of GFRP as structural webs. The height of the trusses is variable being 3.4 m at the elastomeric support and 1.2 m at mid-span. The bottom chord has an innovative shape prominent to the outward of the bridge. The chord has constant height of 350 mm and constant width of 376 mm. The thickness of the bottom-chord varies according with the structural needs. The top-chord has a triangular-shape with constant height and width of 350 mm. The thickness of the chord is constant of 20 mm along the whole bridge. The trusses located on both ends of the bridge have the same triangular-shape as the top-chord previously mentioned.

The cross-section width is 4.6 m and the walkway width is approximately 4.3 m. The deck will be built using GFRP panels 40 mm deep. Two different transverse girders are used, type I 300x150x15 mm made of GFRP and stainless-steel girders. The steel girders have a rectangular shape of 350x300x20mm. The spacing between the GFRP is 1.020 m and the steel girders are placed among them every two trusses. The both end transverse girders are also made of stainless duplex steel. The stainless steel girders are welded to the bottom chord on all the sides to provide lateral stability.

The connection between the bottom chord and GFRP transverse girders is made through bolt connection considered as a pinned connection. The GFRP panels located between the Vierendeel trusses consist of two plates with 4 mm thickness. The GFRP panels are connected to both chords with stainless-steel bolts. The GFRP floor panel is simply supported on the floor girders and the connection is made with standard bolts which are specifically built for these kinds of panels.

The abutments of the bridge are made of reinforced concrete. The height of the abutment is approximately 9.6 meters and it has been built in two different stages. On the first stage, the total height of the abutment is 8.10 meters and a steel sheet has been left embedded for the posterior placing of the steel structure. The final concreting is carried out once the footbridge is located and welded to the steel bearing plate. The width of the abutment is 5,6 meters. Green walls aligned with the abutments help to integrate the footbridge with the surroundings.

2.6. Tarragona Pedestrian bridges

The T-11 pedestrian bridges are a set of 4 similar pedestrian structures that cross the T-11 highway near Tarragona, Spain, completed in 2013. The footbridges are located in different positions along T-11 highway and the two-span continuous Vierendeel truss with span length varying between 19.5 m and 28.5 m (Figure 7). The typical cross-section is 2.85 m wide with a free walkway of 2.12 m. The pedestrian bridges have both curve layout and elevation.



Figure 7. T-11 pedestrian bridges.

The bottom chord has a trapezoidal shape with inclined webs to increase sun light reflection. The thickness of the bottom chord varies among the footbridges depending on the different spans and placing always the thickest over the pile for having the higher negative moments. The maximum thickness used is 18 mm and the minimum 12 mm. The top chord is considered as a structural member that works on tension or compression. The top chord is a steel plate 35mm x 300 mm. The handrail is made of polished stainless steel and it will be placed over the top chord.

The deck is also built with two different kinds of transverse girders. Typical floor beams are I 200 x 100 x10 GFRP girders spaced at 1.1 m. The connection between the chord and the GFRP girders is made through stainless steel bolts which makes a pinned connection. Steel floor girders with rectangular shape are placed every 4.4 m to increase lateral stability of the floor system. The two end transverse girders are also made of steel but the shape differs from the ones located along the bridge. These steel girders are welded to the bottom chord on all sides.

The GFRP web panels located between the trusses consist of one single panel with 4 mm laminate-thickness. This panel is connected with a GFRP plank 4 mm thickness which is glued to the previous one with translucent epoxy adhesive. The GFRP floor panels are mounted over the girders and the connection is made with standard bolts.

The lighting system is integrated inside the trusses giving a minimalist view and guidance for pedestrians along the footbridge. The access to the footbridge is improved by building concrete-ramps on both sides of the highway which will fulfil the current accessibility requirements and will improve the functionality of the urban area.

The end columns will support both the ramps and the cantilever for the footbridge. The piers have a circular cross-section 0.45 m in diameter and approximately 6 m height. The central pier is placed on the central median of the highway and it has a Y-shaped.

3. CONCLUSIONS

Most of the fundamental advances in structural engineering have been related to the use of new materials. The increase in the use of advanced materials in bridge design can partially be attributed to the increasing awareness from Public Administrations to use materials that require reduced maintenance in addition to having greater mechanical resistance. This paves the way for attractive bridge engineering.

The bridges presented in this article illustrate the great possibilities offered by stainless steel and GFRP materials to structural engineering. Even if the cost of the stainless steel is higher than conventional materials (carbon steel and concrete), an economical decision based on life cycle cost of the structure enhances structural solutions with advanced materials thanks to the considerable economical savings from its reduced maintenance.

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Towards Advanced Composite Material Footbridges

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Introduction

The use of fibre-reinforced plastic profiles in civil engineering structures has undergone a significant development over the last decade. From the construction of the cable-stayed footbridge at Aberfeldy, UK (1992), to that of the Pontresina footbridge, Switzerland (1997), some ten further bridges, partially or entirely using composite materials [1, 2 and 3], have been reported in technical literature. Most of these recent structures are truss-type bridges using glass-fibre-reinforced plastic (GFRP) pultruded profiles.

The footbridge presented in this paper is located about 2 km from the city of Lleida, in Spain, and was built to cross a roadway, a railway line and the new projected high-speed railway line between Madrid and Barcelona. The owners required a new pedestrian structure with minimum maintenance and which would be easy to erect. The footbridge was completed in October 2001.

The proposed and accepted construction solution resulted in an innovative design using GFRP pultruded profiles which have no magnetic interaction with the electrified railway line, minimum maintenance costs and was easy to build (Fig. 1). Thanks to its light-



Fig. 1: General view of the entire GFRP footbridge

ness, it took only 3 hours to complete the erection of the bridge to its final position. The principle factor contributing to the construction of this bridge was the creative spirit of all those involved in this project.

General description

A main problem was that of finding an appropriate structural form to span the required 38 m length using standard GFRP profiles. The final structure is a double-tied arch of 38 m span-length with a rise of 6.2 m (span/rise \approx 6) and 3 m wide (Fig. 2). The arch configuration was chosen to minimize serviceability problems due to the low modulus of elasticity of GFRP profiles. The

arches are inclined 6° to achieve a more pleasant appearance (Fig. 3). The total weight of the bridge is approximately 19 t. It is possible that it is the longest span bridge in the world using this type of structure.

All of the profiles are made of fibre-reinforced plastics using continuous E-glass fibres combined with woven and complex mats with a minimum glass-fibre content of 50%. The matrix is made of isophthalic polyester. The modulus of elasticity in the longitudinal direction ranges from 23–27 GPa, depending on the type of profile. Its tensile or compressive strength in the longitudinal direction is 240 MPa and its strength in the transverse direction varies from 50 to 70 MPa.

Both arches and the tied longitudinal members present a rectangular hollow cross-section made up of two U 300 · 90 · 15 mm profiles joined with glued flat plates of 180 · 12 mm to form a beam tube (Fig. 4). The supplier of the profiles carried out full-scale testing

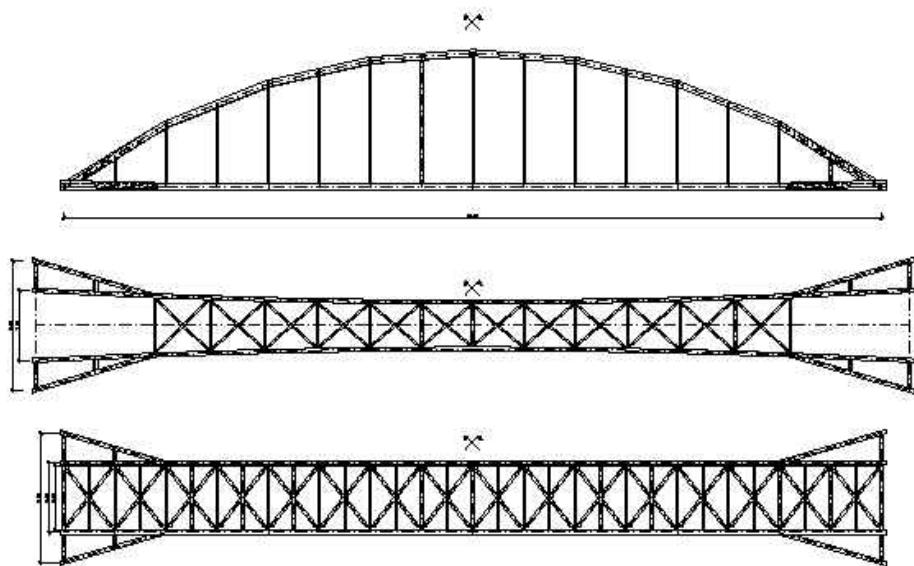


Fig. 2: Elevation and plan views of the footbridge



Fig. 3: Elevation and view of the footbridge from the west ramp

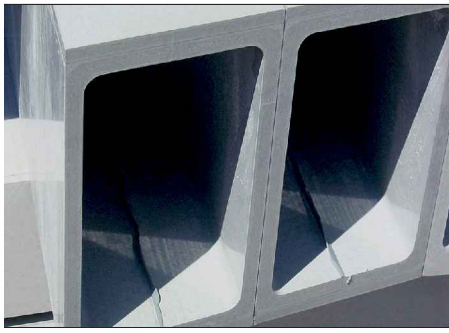


Fig. 4: Arch profiles



Fig. 6: Connections between floor profiles



Fig. 7: Connections in the arch

to verify the beam joints using the proposed epoxy adhesive. In order to reduce horizontal deformation of the arches due to wind pressure, these elements are forked out into two branches using the same profiled sections (Fig. 3).

The hangers are I-profiles of 160 · 80 · 8 mm. The arches are connected by square tubes of 100 mm size and are of various thickness (6 to 8 mm).

The deck is made up of transverse I-beams of 200 · 100 · 10 mm, spaced at 0.6 m and directly supporting the 4 cm thick deck panels which form the transit or roadway surface. A bracing system, to avoid distortion, was designed using diagonal U-section members of 160 · 48 · 8 mm as a typical cross-section (Fig. 5).

The chief problem with GFRP structures is the design, construction and assembly of the joints due to the anisotropic behaviour of the FRP profiles. As a result of the lack of experience



Fig. 5: Floor system

with glued connections on bridges, all joints are bolted using stainless steel brackets and bolts (Fig. 6 and 7). Diagonal elements were added in the design, joining the nodes of the arches and the tied longitudinal members, to improve the dynamic behaviour of the bridge. To reduce its visual image, stainless steel cable elements of 12 mm in diameter were selected.

Access to the arch bridge was created using reinforced concrete ramps conceived as a continuous beam of 10 m maximum span-length and 0.6 m in depth. The slope of the ramps is limited to 8% to guarantee complete accessibility for disabled persons.

Design criteria

Structural static and dynamic analyses were carried out using a three-dimensional bar model and assuming elastic behaviour.

The design had to comply with the Serviceability Limit States required by the Spanish Bridge Design Code. The bridge has been designed for a nominal uniform load of 4 kN/m². The partial safety factors for material properties adopted to verify the Ultimate Limit States were: 2 for normal stresses and 3 for shear stresses. For buckling stability verification, the mean modulus of elasticity was reduced by a factor of 2. The design of most of the elements was governed by the Limit State of Deformation and, in some of the elements of the arches, by buckling stability.

Deflection under frequent loads (2 kN/m²) is about 24 mm (L/1580). Static and dynamic tests were performed before the erection of the bridge in its final position. During the static tests – using 1.6 t water containers, each equivalent to 2 kN/m² mean load – the maximum deflection reached was 26 mm. Residual deflection was 7 mm and was

probably due to the adjustment of the bolts and connections. The structural behaviour was practically linear (Fig. 8 and 9).

Special attention was given to the dynamic behaviour. First frequency (flexural mode) obtained in the analysis was 2.69 Hz. Maximum acceleration was limited by introducing diagonal elements joining arches and longitudinal tied elements to obtain a stiffer structure. The first frequency, measured during the dynamic test, was 2.75 Hz and viscous damping was 2.5% to 3% of critical damping.

The parameters measured during the test show that the structure is considerably stiffer than indicated by theoretical predictions. This is due to the profiled members having a higher deformation modulus than was presumed in the design stage and, also, to the extra stiffness of the connections (which, in some cases, were rejected in the design stage).

To avoid fractures in the rectangular tubes of the arches and the tied longitudinal beams, some of the joints were filled with a mortar of sand and resin. In the diagonal elements, PVC blocks were used for the same purpose. Due to the complex geometry, in some cases it was impossible to fill them with either mortar or PVC blocks. It should be noted that the higher temperatures induced by the use of considerable volumes of resin mortar may end up damaging the profiles. Detailed analyses of joints without mortar were carried out using finite element models including steel brackets. The purpose was to quantify the stresses and deformations produced by the pressure induced by the bolts.

Construction

The structural elements were manufactured in Denmark and transported

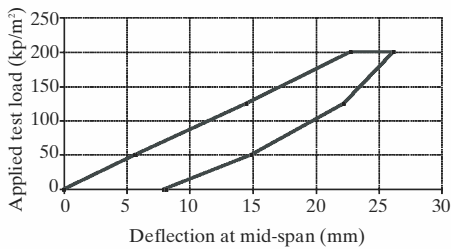


Fig. 8: Mid-span deflection measured during static test



Fig. 9: General view of the load static test made before the final erection of the bridge

to Spain for assembly. The maximum length of the elements transported is 9 m. The bridge construction process was as follows:

- construction of the reinforced concrete end-ramps
- construction of temporary columns next to the ramps so as to permit mounting the complete FRP structure
- the assembly of the deck's members
- assembly of the vertical elements and arches
- the painting of the FRP profiles (in white and blue)
- the partial demolition of the temporary columns so as to transfer the loads to the end piers, reproducing the final support configuration to permit performing static and dynamic tests
- the installation of the structure spanning a busy railway line within a 3 hour time-limit (Fig. 10).

The assembly was carried out by 8 people working over 3 months. The low weight of the bridge coupled with the possibility of using simple hand tools for machining the required adjustments, made the bridge assembly much easier. Some difficulties arose during the erection of the arches due to their complex geometry requiring minimum tolerances in the length of the profiles and the geometry of the steel brackets. This resulted in some adjustments on site.

Conclusions

The positive interaction between the administration, the contractor, the sub-contractors and the design engineers was the principle factor in making this innovative footbridge a reality.

The range of application of advanced fibre-composite materials is very wide, particularly when minimum maintenance, lightness, transportation facilities, no magnetic interaction or quick erection times are required. The initial cost due to material supply and design is higher when compared with traditional steel-based solutions, however, considerable savings are made in construction and maintenance.

The development and future of advanced composite materials for architectural and civil engineering structural applications will depend basically on the development of new structural forms and element-joining techniques. Structural codes could help to spread the use of full advanced composite plastic structures but regulations of these standard documents could also have a negative effect on the creativity of structural engineers.

Engineers possess a magnificent potential knowledge regarding the behaviour of materials and structures but aesthetics should also be taken into account as well as structural performance and economy. All this could easily be done by simply making an extra effort during the conceptual design stage. This footbridge demonstrates that advanced composite materials can be easily introduced into most types of structural forms thus taking advantage of their outstanding mechanical and chemical properties.



Fig. 10: Erection of the bridge

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SEI Data Block

Owner:

Gestor de Infraestructuras Ferroviarias.

Structural design:

Juan A. Sobrino, Javier Jordán and M^a Dolores G. Pulido, civil engineers PEDELTA

Contractor:

UTE Lleida. RUBAU Construccions – COPASA, Spain

Subcontractor:

Fiberline, Denmark

Total cost (USD): 325 000 USD

Cost of composite structure (USD): 270 000 USD (2350 USD/m²)

Service date: October 2001

Stainless Steel Road Bridge in Menorca, Spain

Juan A. Sobrino, Dr. Eng., PEDELTA, Barcelona, Spain

Summary

One of the most interesting things in the development of bridge engineering is the exploration of new structural materials, like for example stainless steel with its excellent mechanical properties, magnificent durability and aesthetic possibilities. The use of new structural materials in bridge engineering constitutes a metaphor to the innovation and, at the same time, a vindication of the enormous value of engineering, as an impelling element of the development and progress of the society, building bridges for the future and paving the way to the ones that follow.

This paper describes a composite stainless steel road bridge, recently built in Cala Galdana (Menorca), being the first road bridge in Europe and probably worldwide using stainless steel for the structure.

Introduction

The island of Menorca was declared a unique biosphere by UNESCO thanks to the natural surroundings and its rich historical and ethnological heritage: an outdoor museum. Cala Galdana is, with its shell form, 450 m long and 45 m wide, one of the most beautiful beaches of the island. The surroundings are only partially urbanized, and they contribute to the attractiveness of the island to tourists.

Algendar river terminates at the beach of Cala Galdana and it has been crossed for the last 30 years via a reinforced concrete bridge approximately 18 m long. Due to its advanced state of corrosion, induced by the marine atmosphere, and an important support settlement in one of the abutments, the owner decided to substitute it by a new bridge. The new bridge should span the entire width of the old river, more than 40 m, fitting harmoniously in the natural surroundings and making use of a material with great durability and minimum maintenance.

During the design process, different structural and material alternatives were analysed. Eventually, a duplex stainless steel arch structure was chosen due to

its high resistance to corrosion from the marine atmosphere, as the solution that better responded to the owner's requirements. The new bridge has become a landmark for the island, thanks to the technological innovation of using stainless steel.

The solution has been designed fulfilling four explicit objectives: environmental respect (during construction and in service: recovery of the old river bed), high durability, minimum maintenance and a symbol of advanced technology (*Fig. 1*).

Stainless Steel as Structural Material

Though the variety of the stainless steels is enormous, it is possible to find more than 100 types of frequently used grades. They contain as a common denominator at least 11 % of chromium that, with the presence of other components as nickel, molybdenum or nitrogen, among others, gives a steel alloy that exhibits a great corrosion resistance, ductility and mechanical strength, even when exposed to high temperatures, as well as excellent aesthetic possibilities and easy maintenance and cleaning. The chromium contained in the stainless steel forms a soft, stable and transparent layer of chromium oxide (Cr_2O_3) on the surface (passivation layer) that avoids corrosion.

Four types of stainless steel exist according to their metallurgical structure: ferritic, austenitic, duplex and martensitic. Duplex stainless steel is an austenitic-ferritic alloy with a microstructure of great corrosion resistance, excellent



Fig. 1: General view of the bridge over Algendar river

Mechanical property	Stainless steel Duplex 1.4462 (Minimum specified values)	Stainless steel 1.4404 (ASTM-316L)	Carbon steel S-355	Stainless steel Duplex 1.4462 (used in Cala Galdana Bridge)
Tensile strength (MPa)	640	530	510	767
Conventional yield stress $f_{0,2}$ (MPa)	460	220	355	535
Elongation (%)	25	40	>15 %	35

Table 1: Mechanical properties at 20° C. Minimum specified values of three different steels

ductility and mechanical characteristics superior to the great majority of carbon steels. Thanks to their high strength, duplex steels are suitable for application in bridges and footbridges [1] [2]. With the existence of a wide range of duplex steel grades, the selection of the most suitable type clearly depends on the ambient aggressiveness, type of corrosion, mechanical properties, types of surface finish, and so forth.

Stainless steel, unlike the conventional carbon steels, presents a mechanical nonlinear behaviour, even under reduced stress values, without having an elastic limit strength clearly defined. However, the stress value associated to a strain of 0,2% has been adopted as a conventional yield stress ($f_{0,2}$). For hot rolled plate, and taking as an example the duplex steel 1.4462 used in the bridge of Cala Galdana (Menorca) described in this article, mechanical properties of the material are summarized in Table 1, comparing it with the stainless steel 1.4404 (ASTM 316 L) and the carbon steel S-355.

Surprisingly, in spite of the impact that stainless steel has had in industry, naval construction, architecture or consumer products for more than 50 years, its presence in civil engineering and, in particular, in structures, has been virtually nonexistent until just a few years ago. Nevertheless, there have already been built some very interesting footbridges [2].

Bridge Description

The overall length of the bridge is 55 m with a 13 m wide deck. The deck allocates 2 lanes of road traffic (7 m) and two lateral sidewalks, each 2 m wide that allow the pedestrians to enjoy the panoramic views from an excellent location.

The main structure consists of two parallel arches with an intermediate deck. The arches and the deck join at the

abutments by means of an inclined strut that takes the horizontal component of the arch axial force and, consequently, significant horizontal forces are not transferred to the abutments.

Substructure

The soil conditions for foundations of the two abutments are very different. Whereas in abutment 1, on the right riverside, the resistant substratum (Miocene limestone) is at a depth of more than 40 m, in the opposite abutment the limestone appears at a depth of only about 4 m.

Abutment 1 is a big reinforced concrete block, with a footprint of $11,4 \times 9,5 \text{ m}^2$ and 3,8 m high, supported on 14 prefabricated concrete piles of $0,4 \times 0,4 \text{ m}^2$ and 42 m long. As an aesthetic feature, the visible surfaces have been inclined to integrate them into the embankment and horizontal shallow channels have been spaced at 15 cm intervals to avoid large smooth surfaces. Abutment 2 is directly founded on surface limestone. Its dimensions are greater than those of Abutment 1, with a footprint of $11,5 \times 13 \text{ m}^2$ and 7,2 m high.

Each abutment supports the bases of the parallel arches and the two longitudinal beams of the deck. The arches are supported on POT bearings and the beams on laminated elastomeric bearings. In order to avoid the vertical displacement of the deck with respect to the abutment, four vertical anchorages (constituted by four unbonded post-tensioned cables with 12 strands of 15 mm) were applied. The inclined struts that connect the base of the arch and the end of the deck have been recessed into the front face of the abutment (Fig. 2).

Structure

The structural scheme is constituted by two parallel arches with a free span of 45 m and an intermediate deck. The



Fig. 2: Abutment 2. view of the completed element

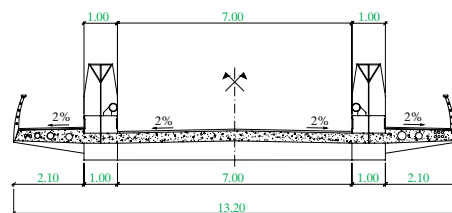


Fig. 3: Typical deck cross-section

main structure is made of duplex stainless steel grade 1.4462, which exhibits a high resistance to corrosion by chlorides. The deck is made of reinforced concrete connected to a series of transverse beams (Fig. 3).

The arches rise to a total of 6 m (relation span/rise = 7,5) and they are tied to the deck by means of two connected longitudinal beams. These longitudinal beams are again connected by means of transverse beams (Fig. 4).



Fig. 4: View of bridge from below

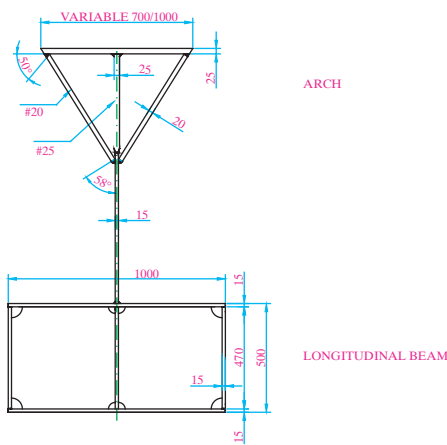


Fig. 5: Typical cross-section of the arch and longitudinal beam

The arches have a triangular cross-section (Fig. 5) with a central web. Their depth is 0,70 m - constant throughout their overall length. However, the width of the section varies between 0,70 and 1 m. The central web of the section is transformed into a cellular plate that allows connecting the arch with the longitudinal deck beam. The longitudinal beams are rectangular hollow sections of 1 m × 0,5 m, constituted by plates with varying thicknesses between 15 and 25 mm. In the central zone with the arch above the deck, these beams have a central web that is connected to the web of the arch, allowing direct transfer of the vertical loads of the longitudinal beam to the arch.

The transverse beams, spaced at 2 m, are formed by rectangular cross-sections 0,25 m wide and with a variable depth varying between 0,50 and 0,57 m (to obtain) the deck cross-slope of 2 %, constituted by plates of 10 and 12 mm. These beams are structurally connected to the reinforced concrete slab, having an average thickness of 0,30 m, by means of Bernold type studs of 20 mm in diameter.

In order not to transfer the horizontal component of the arch axial force to the abutments, two inclined struts—connecting the base of the arch and the end of the longitudinal beam have been designed, which are anchored at the top of the abutments. The struts have a rectangular hollow cross-section, with outer dimensions of 1 m × 0,5 m, formed by plates of 20 and 25 mm thickness, internally stiffened in both longitudinal and transverse directions.

One of the most difficult connections is the one between the inclined strut (of rectangular cross-section) and the

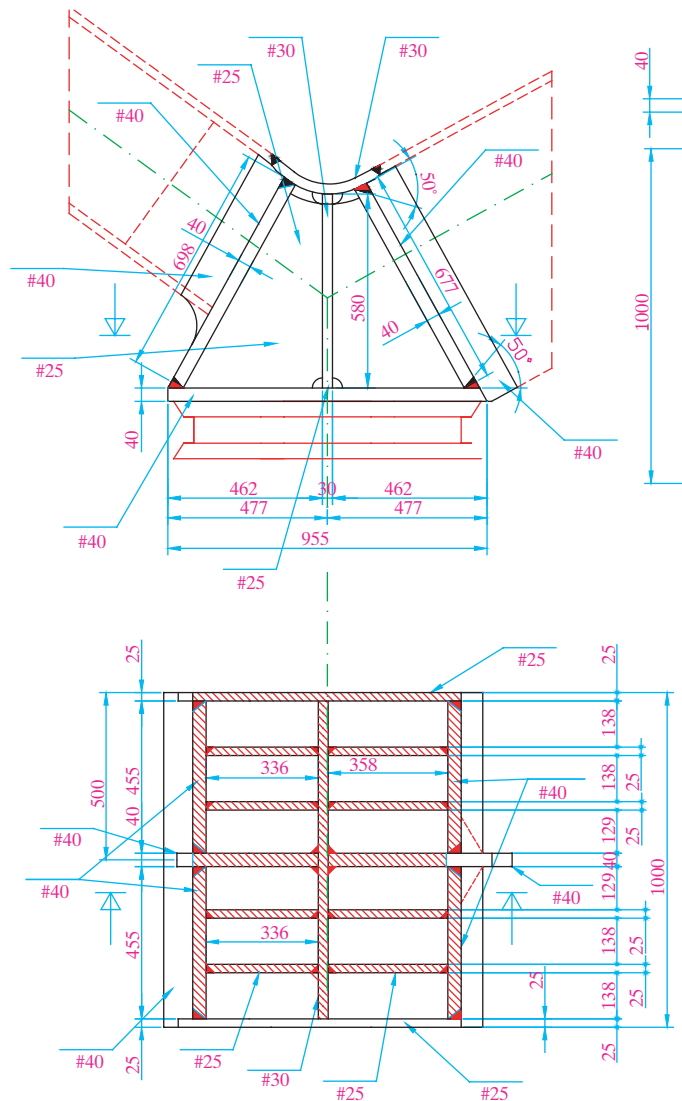


Fig. 6: Joint between strut and arch

base of the arch (of triangular cross-section). This element is directly supported by the pot bearing (Fig. 6) and is strongly stiffened.

The lateral sidewalks are separated from the road by the arches (Fig. 4). These sidewalks are supported by means of a reinforced concrete slab supported on transverse cantilever ribs every 2 m connected to the longitudinal beam.

The railing has been designed with wooden banisters with an elliptical

cross-section, supported by posts of curved geometry made of stainless steel every 2 m joined to the end of the transverse ribs as if it was only one piece.

Structural Behaviour

The analysis and design of the bridge has been carried out using the criteria from Eurocode 3, part 1.4 [3], including consultation of bibliography and existing recommendations from European associations [4] [5].

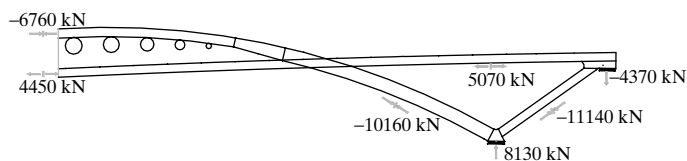


Fig. 7: Distribution of reactions and axial forces (kN) in the most unfavourable service combination

The structural behaviour of the bridge is a self-anchored arch that does not transfer horizontal reaction forces to the foundations. In Fig. 7 the reactions as well as the transfer of axial internal forces among the main elements have been illustrated.

The structural calculations have been made with a standard finite element programme, developing diverse models or adjustments to contemplate the phenomena of softening of the stainless steel under stresses over 60 % of the conventional elastic limit (0,2 % proof stress: $f_{0,2}$) and the cracking effects in certain zones of the reinforced concrete slab. The general model combines bar type and shell elements.

The steel stresses have been limited to 75 % of $f_{0,2}$ for the combination of frequent loads and to 90 % of $f_{0,2}$ for the characteristic combination.

Construction Process

The works of the bridge began in October 2004, starting with the demolition of the existing bridge, and were completed the first week of June 2005.

Processes of construction with stainless steel are similar to those used for carbon steels but non identical, adopting specific techniques for cutting, bending, forming, welding and finishing. Welding consumables must also be specific to the stainless steel grade to guarantee equal mechanical and corrosion properties to those of the base material.

Welding techniques used were with shielded metal arc welding (SMAW) using an inert gas with covered electrode, metal inert gas (MIG), flux cored arc welding (FCAW) and submerged arc welding (SAW) [6], without preheating and not exceeding a temperature of 150° C between two consecutive passes. Welding produces an oxidation of the base metal and a significant change of surface colour and the appearance texture that should be corrected by means of a later treatment. This aspect is essential

to guarantee the desired surface finish, colour and texture. After removing solid slag in the weld, a chemical treatment (pickling) has been applied by means of a pickling paste constituted by acids hydrofluoric and nitric. Its application, during 4 hours, allows the removing of contaminants and oxides generated during welding and facilitate the formation of the passive layer. Finally, in order to guarantee a uniform finished surface of the pieces, a blasting treatment with high pressure using glass micro-spheres has been applied.

The contact of the stainless steel with other metals during the manufacturing or in its definitive location can cause galvanic corrosion. For this reason, manufacturing and assembly of the structural parts was carried out in zones where it does not come in contact with carbon steel.

The bridge was assembled on site by means of crane, placing 8 sections on temporary supports for later welding (Fig. 8).

Once the construction of the bridge was completed, a static load test was carried out, considering different load stages,

and measuring essentially vertical deflections. The structure presents a stiffer behaviour than expected. The measured deflections were about 80 % of the theoretical values, obtained with an average value of the modulus of elasticity of $E = 200$ GPa. The deflections recovered elastically practically in their totality. Considering the results of the quality control of the steel, which affirms that the secant modulus of elasticity at 0,2 % is 16 % superior to the one considered in the calculation model, explains the difference of deflections measured in the test of load.

An exhaustive quality control process has been undertaken, increased by the innovative character of the material, having intensified all the internal controls of the welds both off and on site with techniques such as ultrasonic testing, X-rays and magnetic particles. The measured values of the stainless steel mechanical properties at the quality control turned out to be greater than the ones specified in the design and the Codes (Table 1).

Conclusion

The fundamental advances in structural engineering have always been related to the use of new materials. The increase in the use of advanced materials in bridge design can partially be attributed to the increasing awareness from Public Administrations to use materials that require reduced maintenance in addition to having



Fig. 8: Assembly of the steel structure

greater mechanical resistance. This opens up an attractive way for bridge engineering.

Cala Galdana Bridge, a landmark of Menorca, illustrates the great possibilities offered by stainless steel to structural engineering. Even if the cost of the stainless steel is sensibly superior to that of conventional materials (carbon steel and concrete), an economical decision based on life cycle cost of the structure enhances structural solutions with stainless steel thanks to the considerable economical saving from its reduced maintenance.

Acknowledgements

The positive interaction between the client, contractor, subcontractors and the consulting engineers has made this innovating project a reality. Special thanks to the *Consell Insular de*

Menorca for its support and promotion of the application of innovative technologies to bridge engineering.

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SEI Data Block

Owner:
Consell Insular de Menorca
Mobility Directorate

Design and Technical Assistance During Construction:
PEDELTA. Juan A. Sobrino, Juan V. Tirado, Javier Jordan, Xavier Martinez (Civil Engineers) and Agusti Garcia (Industrial Engineer).

Contractor:
FERROVIAL

Subcontractors:
OUTOKUMPU, supply and preparation of plates
ASCAMON, steel fabricator (main subcontractor)
MEKANO-4, stainless steel bearings

Stainless Steel (t): 165 (225 Kg/m²)

Total Cost of the Bridge (EUR millions): 2,6 (including accesses)

Service Date: June 2005

Installed in just three hours

The award-winning GRP footbridge near Lleida, Spain, was custom-built to demanding specifications of the Spanish railway authorities for minimal maintenance, fast installation, and zero magnetic interference.

As the bridge would cross a major rail link, minimising disruption to services was a key priority. Accordingly, the bridge was assembled at the track side and then craned into place, resulting in a railway possession time of only three hours for the complete erection.

The bridge was designed by the Spanish engineering consultant Pedelta and built using structural components supplied by Fiberline Composites.

"Footbridge Award 2005"
The journal Bridge design & engineering

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