Use of composite structures for the reinforcement of pathologies in concrete bridges

I. Pulido Sánchez
Maintenance, Inspection and Refurbishment Department Director
IDEAM, S.A. – T.Y. Lin International Group

F. Millanes Mato
President. C.E.O. of the Board of Directors
IDEAM, S.A. – T.Y. Lin International Group

E. Bordó Bujalance
Structures Department Director
IDEAM, S.A. – T.Y. Lin International Group

S. Salas Fernández-Polanco
Project MSc Civil Engineer
IDEAM, S.A. – T.Y. Lin International Group

ABSTRACT: Composite structures allow a wide range of possibilities for reparation and reinforcement of concrete bridges. The use of this type of structures provides several advantages compared to other methods, such as flexibility, polyvalence, high resistance resistance/weight ratio and ease of execution. Important aspects that must be considered are the joints assembly and geometric tolerances control, as well as the connection between the steel structure and the existing concrete bridge. This paper shows a recent example of this technique of reinforcement designed by IDEAM: the viaduct over the Duero River in the A-66 highway, in Zamora (Spain). This structure, consisting of a concrete box girder bridge that suffered several serious structural pathologies, was entirely reinforced by the assembly of a steel structure on the exterior side of the deck. The steel elements connect with the existing bridge resulting in a structure with double composite action.

1 INTRODUCTION

The article describes the possibilities of the use of steel and composite structures in the repair and strengthening of concrete structures with damages. Although the performance of composite structures for new construction works is well known, it is less common to consider them as a tool in rehabilitation projects. It is the authors' intention to draw attention to the possibilities offered by these solutions.

In addition to an explanation of the problems of such kind of reinforcements, and their advantages and disadvantages, a recent case of application to a structure that underwent an integral rehabilitation, the bridge over the Duero River in the A-66, in Zamora (Spain), is described.

2 USE OF COMPOSITE TECHNOLOGY FOR THE REINFORCEMENT OF CONCRETE BRIDGES

Solutions based on the use of steel as reinforcement material make possible to take advantage of the well-known benefits inherent to this technology, both cases: steel design and when composite structure design.

One of the main aspects that characterizes the use of the composite technology for the repair of concrete structures is the flexibility and versatility. The use of steel, generally giving rise to lightweight pieces that can be assembled by segments, makes it possible for the steel reinforcement to be easily adapted to the existing structure. Moreover, due to its superior mechanical properties, it allows a wide range of repair typologies or solutions such as shear reinforcement in beam webs, increase of bending capacity, local reinforcement for load bridging, etc.

Its use not only allows the reparation of damages in structures with pathologies, but also enables a wide range of complementary actions, including: increasing the resistance capacity of concrete bridges (with or without pathologies) that require it for operational reasons; increasing the span of structures by removing or modifying supports; increasing the width of bridge decks; and many others.

Regarding the construction aspects of the solution, the use of composite structures is frequently an option, which usually means clean, simple and fast assemblies.

As for the aesthetics of composite solutions, the aforementioned flexibility allows minimizing the aesthetic changes introduced in the existing structures. This is because these reinforcements can easily fit the existing geometry and the use of steel allows small reinforcements, thus being very unobtrusive.

In addition, steel can be painted to preserve the initial aesthetic conception of the project, or to introduce pleasant material contrasts in the case of Corten steel.

Another fundamental aspect is the environmental respect and integration. Concerting that, composite structures are usually a good alternative, with a reduced environmental impact due to their simplicity of assembly that results in operations with less machinery, less affections to the existing elements in the shadow of the bridge and lower discharges to the environment.

On the side of the disadvantages when considering its use, we can cite the cases of bridges with complex geometry (curved bridges, variable edge bridges, structures without flat concrete faces, etc.).

The difficulty lies in the correct definition of the geometry (in spite of the existing advanced tools for collecting data), in the manufacturing process, and especially in the on-site assembly, where the strict tolerances may make other solutions more adequate.

Another point to be considered, which is discussed below, is the need to connect the new steel structure to the concrete bridge in order to achieve the transmission of forces and allow them to work together as a composite structure. The need to connect steel and concrete can lead to complex on-site operations, such as hydrodemolitions, drilling operations, cutting of steel pieces, etc.

Finally, while workshop fabrication is associated with precise quality control and allows the execution of high-quality welds due to execution conditions, on-site assembly may require complex welds or welds that need to be executed under more difficult conditions. These can make the solution more expensive due to lower yields and weld control requirements.

3 COMMON APLICATIONS

Composite structures have numerous applications in reparation of concrete bridges. The most common are listed below.

3.1 *Shear and flexural reinforcement*

It is well known that concrete bridges with strong damages or with needs to increase their operating loads may require flexural and/or shear reinforcement.

For example, when designing a positive bending reinforcement, the solution is simple, and it can consist of arranging steel plates on the underside of the concrete beams or slabs. To work together as a composite section, it is necessary an adequate connection of both elements.

When there is any pathology that reduces the shear capacity of the bridge, the composite structures allow a clean solution by simply attaching steel webs connected to the concrete beams. that present a lack of shear capacity.

Since these reinforcements are mainly placed in the support areas, one of the difficulties that usually arises is the stresses transmission from the new structure to the substructure. It is usually necessary to carry out load transfer operations with hydraulic jacks and to change the support points, which in some cases requires the enlargement of piers and abutments due to space requirements.

A common case related to the above is the repair of pathologies in beam ends. These elements are often susceptible to structural damage as a result of water filtration through expansion joints or to the effect of stress concentration due to poor support conditions or design errors. (Fig.1).

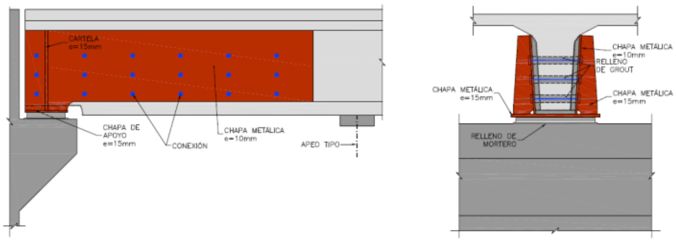

Figure 1. Reinforcement of prestressed concrete beams with steel plates

When the aim is to increase both the shear and bending capacity, it is possible to connect new steel beams to the existing beams or box, so that the compression slab can be used as a resistant element. An example of this solution is the Duero Bridge in Zamora, described below.

3.2 *Reinforcement of piers*

The use of these structures is also applicable in the repair or reinforcement of piers. It is worth citing as an example the Centenary Bridge cable replacement project in Seville (Spain), where the use of composite structures has made it possible to extend the pylon cross section, with the dual purpose of reinforcing them and shifting the position of the future new cable plane outwards.

The pylons of the Centenary Bridge consist of a composite structure formed by a concrete box section to which a steel plate is connected on the outer face.

The cable replacement involves moving the new cables outwards to give the platform a greater width and allow the replacement. In order to be able to move the cables out of position, it is necessary to widen the existing pylons and to reinforce them.

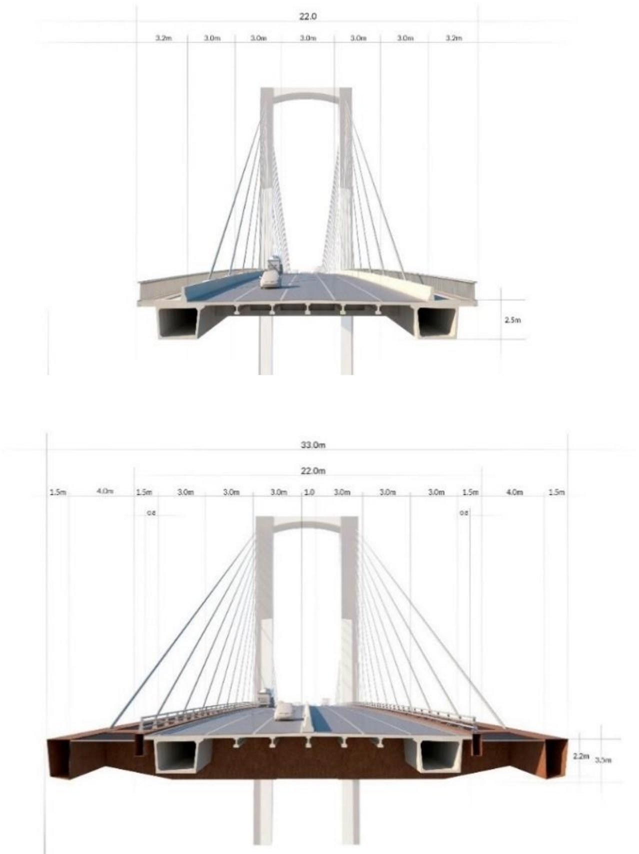

Figure 2. Current cross-section and Cross-section after the replacement of the stay-cables (6 lanes)

The new pylon cross section is formed by a steel box attached to the outer side of the existing pylon. This box is linked to the existing section with a continuous weld along the entire height. It also has some diaphragms connected to the concrete section with prestressing bars. The enlarged section is a composite section from the basement of the pylon up to a certain height, where it is formed by a hollow metal box.

3.3 *Modification of pier location*

In addition to the local repairs and integral reinforcements mentioned above, the use of composite systems allows structural modifications such as widening of decks or piers, increasing the span and eliminating of supports.

An example of this is the increase of the span of numerous highway overpasses in Spain such as the overpasses on the A-7 highway and thus widen the below road to six lanes (Fig.3). The procedure consisted in connecting steel beams to the existing concrete slabs, which are supported on the new pile axes of the structure. The steel beam has a double function: on the one hand, it allows to collect the reaction of the original concrete deck and transfer it to the new support axis without modifying the stress and deformation diagrams of the existing structure and; on the other hand, it collaborates in the resistance of the overloads once both structures are linked. The connection of both elements is carried out with prestressing bars in the areas close to the original support axis. With this methodology, it can be achieved span increases of between 20 and 35% of the original span.

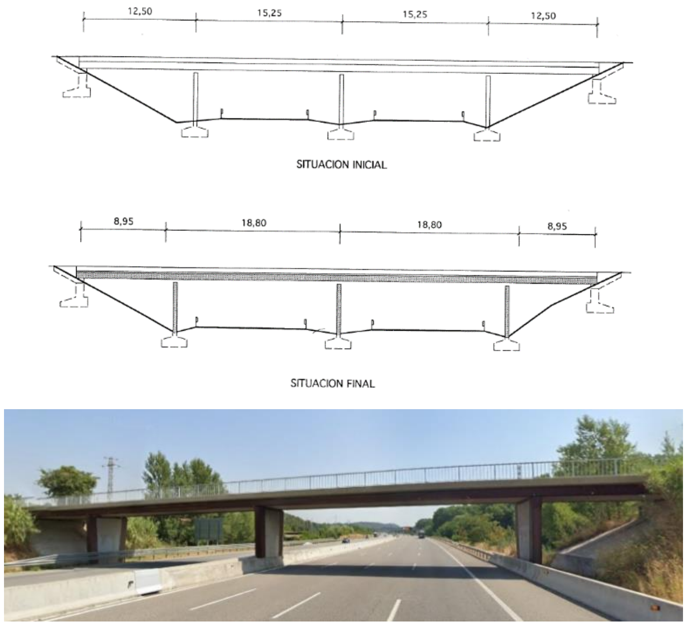

Figure 3. Increase of the bridge span.

4 CONNECTION TO THE EXISTING STRUCTURE

When we talk about the repair of concrete bridges using the aforementioned composite systems, one of the main aspects to take into account is the connection, which is essential for the behavior as composite structure.

When designing the connection of the steel plates to the concrete member, the designer must consider whether a localized connection or a distributed connection is needed. This will depend on the type of stress transmission and the type of reinforcement designed.

For example, if the aim is to transmit the forces from the concrete deck to a steel element at a specific point, as in the above-mentioned extension of spans in overpasses, a localized connection at the point of interest will have to be used.

The distributed connection, commonly used in new composite structures, can be used in situations where the repair consists in taking advantage of an existing concrete slab by incorporating steel beams and make both elements work together as a composite section, or in flexural reinforcements with long plates where there is enough space of this kind of connection.

The fact of making the steel connection to the concrete member does not ensure the correct behavior as a composite structure. One of the key aspects to be verified is if the existing structure can transmit the required localized stresses, as well as if the existing reinforcement in the concrete section is enough to ensure such transfer.

There are several connection solutions available depending on the type of connection sought:

In cases where a pure shear connection is needed, the elements usually used are stud connectors, channel connectors, angle connectors, tendon connectors, perfobond connectors or T-shape connectors. The arrangement of these types of elements requires solving the problem of how to embed these elements in the existing concrete.

Figure 4. Hydrodemolition of a concrete slab to house stud connectors.

One of the solutions frequently used is the partial hydrodemolition of the slab to create space for the connection and its subsequent concreting (Fig.4). This method presents several disadvantages or difficulties, such as the need to demolish the slab in alternative areas to ensure the structural integrity during the works.

On the other hand, for the arrangement of this type of connectors, it is possible to drill independent holes in the concrete deck to weld each of the connection elements.

The shear forces can be transmitted by friction between the concrete and the steel through connections with bolts or prestressing bars as indicated above in the case of the piers of the Centenary Bridge.

When designing a connection based on channel connectors (Fig.5), we are talking about a case of direct load transmission, in a localized area. Comments already made on the verification of the local area against point load are applicable. The design must take into account the possibility of reversible loading, since direct contact transmission is unidirectional. They may result in steel connectors of significant dimensions requiring complicated assembly.

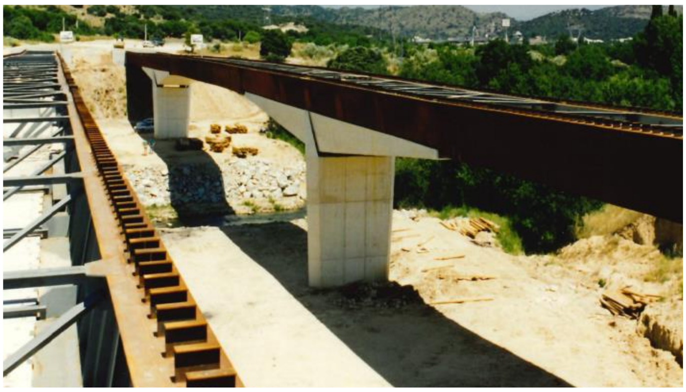

Figure 5. View of the connector at Retamar Viaduct (Spain)

Connection can be also made by rebars welded to the plates and embedded in a section of concrete, or directly anchored to the existing structure with drilled holes.

5 CASE STUDY: INTEGRAL REINFORCEMENT OF THE VIADUCT OVER THE DUERO RIVER ON THE A-66 HIGHWAY

The recent rehabilitation of the Viaduct over the Duero River is an example of a reinforcement of a concrete bridge with steel beams, transforming it into a composite bridge.

5.1 *Structure description*

The viaduct over the Duero River (Figs.6 and 7), consists of two twin structures 277.00 m long and 11.70 m wide. The layout is slightly curved. Each of the structures has six spans with five intermediate piers. The spans are 34.50m + 36.00m + 49.50m + 72.00m + 49.50m + 34.50m.

Piers P1, P2 and P5 are made of reinforced concrete and have a rectangular cross-section cast on site. Piers P3 and P4 consist of an on-site concrete plinth, on which are supported two inclined precast concrete props that connect monolithically with the deck, forming a triangular cell.

Figure 6. General view

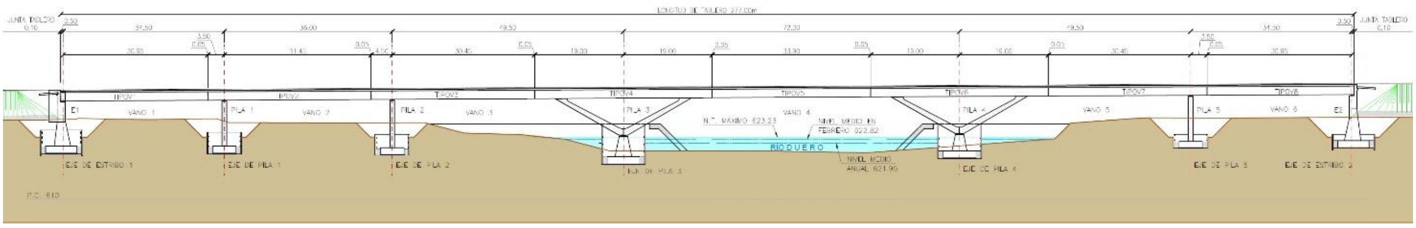

Figure 7. Elevation view of the structure

The deck consists of 1.80 m thick precast concrete post-tensioned box girder, pre-slabs and a reinforced concrete top slab.

5.2 *General description of the existing problem and justification of the mixed solution*

The structure over the Duero River presented a series of generalized damages that affected its structural safety, so it was needed to provide a complementary resistant mechanism to ensure the adequate behavior of the deck. The main pathologies detected were as follows:

- Cracking of the webs of the precast concrete beams. All the beams had a series of longitudinal cracks running along the structure. These cracks were monitored, so it was possible to verify that they were live cracks.
- Opening of joints between beams. The connection between consecutive box girders were made with prestressing bars. During the different inspections, it was verified that the joints of the central span were opening up over the years.
- Evolution of the deflection in the center span.

The state and the resistant behavior of the structures were uncertain due to the pathologies indicated and it led to the decision to reinforce the structure.

Within the study of the possible repair alternatives, concrete solutions were analyzed, but discarded, because they either required the restoration and reinforcement of the damaged areas and did not guarantee the complete reestablishment of the bridge's resistant capacity, or they were difficult to execute and with a significant modification of the aesthetics of the original structure, as well as suppose a significant increase in weight.

The demolition was studied and discarded for various reasons, such as the significant impact on traffic on the A-66, the long execution time, and the significant environmental impact.

Once the aforementioned options were discarded, the alternatives that steel could provide for the repair were explored, thinking fundamentally of the flexibility, ease of execution and formal respect that this material could provide.

Finally, the structural solution consists of steel beams attached to the existing concrete beams, as well as to the bridge slab, making a doble action composite structure with the capacity to resist both the existing permanent loads and the overloads (Fig.8).

Among the aspects that led to the choice of this solution were:

- It allowed to preserve the existing structure, avoiding the demolition of the affected elements.
- It allowed to take advantage of the resistant capacity of the upper slab and the lower board of the box girder, which were in a good state of preservation.
- Optimization of the use of materials, using only reinforcement structure in the damaged areas (concrete webs).
- Possibility of reusing the substructure of the bridge with only a minimum geometric adaptation to ensure the correct transmission of the loads from the steel reinforcement to the substructure. (Fig.9).
- Maintenance the original aesthetics (shape) of the bridge. Although at first it was considered the possibility of using gray painted steel, maintaining the initial appearance of the structure, it was finally decided to use Corten steel, in order to reduce its future conservation needs.
- The designed solution allowed the construction while maintaining one lane of traffic, minimizing the impact on traffic.
- All the works could be carried out from the platform itself or from land, and in no case was it necessary to invade the Duero riverbed.

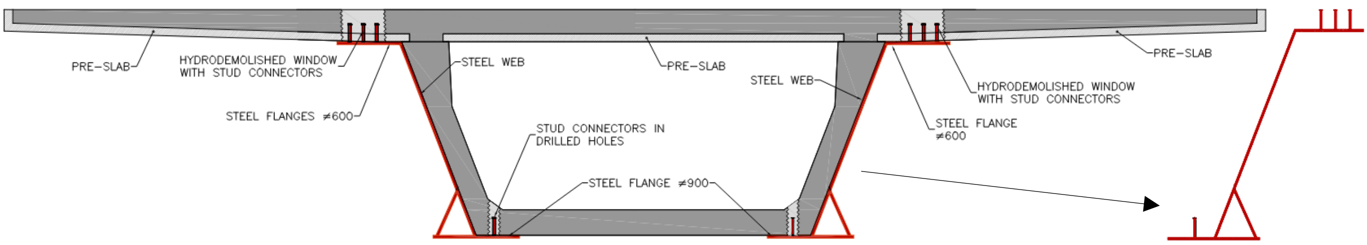

Figure 8. Cross section of the proposed solution and detail (left) of typical cross section of the steel reinforcement.

5.3 *Adaptation of the substructure*

The first work that had to be undertaken was the adaptation of the substructure to receive the stresses transmitted by the new composite structure.

In the case of the abutments, the axis of the existing supports had to be moved forward in order to support the new steel structure.

The reduced space in the abutments did not allow place the new supports, so two front columns connected to the abutment walls were built.

In the case of the conventional piers, due to the geometry of the steel reinforcement, the position of both supports was shifted laterally outwards to allow the steel webs to rest on them. For this reason, the piers were widened.

Figure 9. View of the lateral screeds in conventional piles.

5.4 *Metal beams: erection, assembly of sections, connection to existing structure*

As mentioned above, the reinforcement solution designed consists of two steel webs connected to the upper and lower slabs to create a doble action composite structure.

The main challenges of the project were to fabricate a steel structure that would adapt to the original structure, curved and with different deformations in each span, to make the steel structure continuous along the length of the bridge and to connect them to the existing structure without damaging the resistant elements.

The erection of the steel reinforcement began with the load transfer to a hydraulic jack system in order to place the abutment and pier segments. These segments, of reduced dimensions, were the ones that had to rest on the new elastomeric bearings to transmit loads from the steel section to the substructure.

These segments were assembled in half-sections (one per side) from the ground with a single crane and, later on site, both sides were connected with a weld joint.

Once all the abutment and pier segments had been assembled, the load was transfer from the hydraulic jacks to the new elastomeric bearing, installed in the aforementioned screeds.

Figure 10. Pier segments.

Figure 11. Welding works at abutment segments.

When those operations were finished it was time to start with the erection and assembly of the span segments (Fig.12).

These segments covered the entire span, except for the span over the river and the adjacent spans where, due to the load limitation of the cranes, the spans was split into two segments. To ensure that the steel beams would fit the existing deck, a 3D geometric model of the deck was made using laser scan technology. This model allowed the fabrication according to the existing geometry, providing them with the necessary curvature to adapt to the existing geometry.

Figure 12. Steel reinforcement beams.

In order to materialize the composite behavior, it was necessary, as explained above, to connect the steel beams to the existing concrete structure. The connection of the steel top flange to the top slab was solved by stud connectors. For this purpose, a series of "windows" were made in the cantilever wing by hydrodemolition of the entire slab depth to accommodate the connecting studs (Fig.13).

The connection of the bottom flange to the bottom slab of the precast beams was also made with studs, but, in this case, diamond core holes were drilled in the slab to accommodate the studs. These studs were welded on site using a stud welding gun.

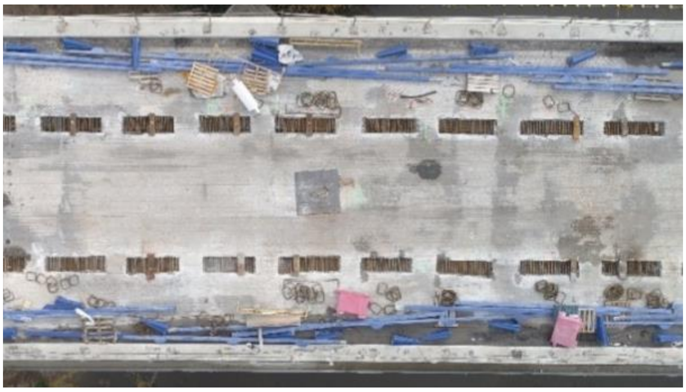

Figure 13. Plan view of the structure with the windows executed in the cantilevers to house the connecting bolts of the top flange.

Figure 14. Bottom view of the deck with the windows in the cantilever and the holes in the bottom slab to accommodate the connection studs.

Since this was a reinforcement of an existing bridge, conventional assembly of the steel beams directly by crane was not possible. Therefore, special structures had to be designed to pick up the steel segments and move them below the cantilever to their final position (Figs.15 and 16).

Once placed in their final position and adjusted to the existing structure, the segments were fixed to the concrete deck by temporary anchors so that the cranes can be released. Then, both ends were welded to the pier or abutment segments that had been previously assembled and were already resting on the new bearing supports.

Once placed in their final position and adjusted to the existing structure, the segments were fixed to the concrete deck by temporary anchors so that the cranes can be released. Then, both ends were welded to the pier or abutment segments that had been previously assembled and were already resting on the new bearing supports.

Figure 15. Erection of steel beams

Figure 16. Erection of steel beams

The bottom plate bolts had to be welded in situ from inside the caisson, as indicated. Once welded, the holes were filled with a non-shrink grout.

Next, the interface between the new steel web and the concrete web was filled with a cement grout that avoid that water or other elements could enter and guarantee the durability of the structure.

Finally, the hydro demolished windows of the top slab were concreted with the studs connectors.

5.5 *Assembly of the V-shaped piers*

The viaduct has two V-shaped piers monolithically connected to the deck. It was not possible to transfer loads from the deck to the substructure in these piers with the procedure designed for conventional piers. The proposed solution consisted of transmitting the load from the deck to the concrete pier using a steel plate connected to the pier. The connection was made again with stud connectors.

To accommodate the bolts, holes were drilled along the entire length of the pier. Then, with the use of a drone, all the holes were staked out so that the studs could be welded during the fabrication process with the required precision (Fig.17).

Figure 17. Steel reinforcement at V-shape piers

The main plate was welded to the bottom steel flange of the deck.

Finally, both stud holes and the interface between the concrete pier and the steel plate were filled with a flowable mortar.

Figure 18. View of the V-shaped pier

6 REFERENCES

Martínez, J. *"Ampliación de las luces de 15 pasos superiores continuos postesados, para conseguir el ensanchamiento a seis carriles de la autopista A-7 Barcelona-La Junquera. Tramo Hostalric-Maçanet"*. Hormigón y Acero nº 196. 133-146.

Martínez J., Ladrón de Guevara, *"Ampliaciones de luces de pasos superiores de autopistas existentes. Solución aplicada en la autopista A-7 (by-pass) Valencia.",* II Congreso ACHE.

CEN, European Comitee for Standardization. EN1993-1-8:2005 *"Eurocode 3: Design of Steel Structures. Part 1.8. Design of Joints"*. 2005.

Ministry of Transport. *EAE: Instrucción de Acero Estructural*, Real Decreto 751/2011 de 27 de mayo de 2011. BOE 23-06-2011.

Ministry of Transport. *RPX-95: Recomendaciones para el proyecto de puentes mixtos para carreteras*.

Figure 19. View of the repaired bridge