The Fort York Bridges in Toronto. The first Duplex Stainless-Steel Bridges in North America

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ABSTRACT

In April 2015, the city of Toronto selected a proposal for the Garrison Crossing, formerly Fort York Crossing, project in a design-build competition. The project includes two pedestrian bridges. The awarded design proposal includes an unprecedented technical innovation in North America: the use of Duplex Stainless-Steel on the entire structure. This pioneering use of a forefront technology has provided premium aesthetics within a unique setting in addition to a safe and durable asset for the community. The structure has an extended life cycle, is more corrosion-resistant and requires less maintenance. This paper discusses the concept, detailed design, structural behavior and bridge erection

KEYWORDS: bridge, stainless-steel, arch, aesthetics

1. Use of Stainless-Steel in Bridges. Previous experiences.

Stainless-Steel is the name given to a family of corrosion and heat resisting steels with a minimum content of 11% Chromium and other controlled alloying element additions, each affecting the mechanical and chemical attributes to resist different corrosive environments. Stainless-Steel is recognized as a sustainable material with a lower environmental impact than Carbon Steel (reduced CO_2 emissions due to fabrication, lightweight construction, low maintenance and reuse when deconstructed). It is worth emphasizing that Stainless steel has one of the highest recycling rates of any material.

In addition to excellent durability, stainless steel can exhibit high mechanical properties. It is primarily used in aggressive environments: near marine environments, where exposed to de-icing salts, or in very heavily polluted locations.

There are more than 100 types or grades of stainless-steel which are typically classified in five basic groups: austenitic, ferritic, duplex, martensitic, and precipitation hardening. The duplex stainless-steels are the most appropriate for primary load-carrying members in civil engineering use, as bridges construction.

Due to the high level of alloying elements and processing in stainless-steel, there is an initial cost premium for stainless when compared to traditional carbon steel used in bridges. However, unlike galvanized or painted steel, the naturally-occurring corrosion resistant surface layer means there is no requirement for applying protective painting. Over the lifespan of a structure, eliminating the need for coating maintenance or component replacement due to corrosion, can lead to significant long-term maintenance cost savings (traffic disturbance and maintenance tasks). Moreover, its appearance during its entire service life is almost as recently built. Only easy maintenance works consisting of cleaning their surfaces can keep it almost as new.

Worldwide, the number of bridges being fabricated from duplex stainless-steel as a primary structural component is steadily increasing, especially for pedestrian bridges. In general terms, the strength, ductility, toughness and corrosion resistance of duplex stainless-steel, such as the grade 2205 proposed for the Garrison Crossing Bridges, are higher than a regular carbon steel. The only construction challenges with the use of Duplex Stainless-Steel are related with fabrication (not difficult but different).

The minimum ultimate tensile strength of grade 2205 is 655 MPa and the minimum yield strength 0.2% offset is 450 MPa. The actual measured mechanical properties of the material used in the Garrison Crossing Project are approximately 20% higher.

2 Project Context

The Garrison Crossing project is located just west of the main downtown area of Toronto. It physically links a series of open spaces that extend from deep within the Niagara Neighborhood right down to the Waterfront in Toronto in the Fort York Area-national historic site and birthplace of Toronto. Two new bridges over the railway corridors west of Fort York and pathways provide enhanced connectivity through these open spaces, offering cyclists and pedestrians a pleasant alternative to busy City streets. The City of Toronto, through Create Toronto, the City's real estate and development Corporation choose a Design-Build procurement model to facilitate and optimal and cost-effective construction of this project. The key design challenge was how to achieve an appropriate landmark quality in this special heritage setting, within a very tight budget.

The awarded design proposal includes an unprecedented technical innovation in North America: the use of Duplex Stainless-Steel on the entire structure. The bridges incorporate high quality, durable, natural finish materials throughout, highlighted by state-of the-art stainless-steel components, complemented by other high-quality durable materials. Stainless steel was also used in the reinforcement bars inside the footbridges concrete deck slab.

One of the key challenges was to design and build the bridges over the existing railway corridors, placing the substructure out of the right of way of the rail corridor and keeping a vertical clearance of 7.44 m above the top of rail. The bridges should have also an unobstructed width of 5 m to accommodate both pedestrians and cyclist and are provided with universal access. The bridges cross over two active rail corridors so consideration must be given to protection, safety, and security of both the railway operations and the pedestrians and cyclists using the bridge.

In order to minimize heritage impacts on the cultural heritage landscape of Fort York, the bridge and approach ramp within Garrison Common at Fort York is to have a minimal footprint.

3 Project Description

The bridges had to be designed for a 75-year service life in accordance with the Canadian Bridge Design Code [1]. The state-of-the-art Design Guidelines and Codes for the structural Stainless-Steel members were also considered [2], [3]. Durability was an especially important issue to consider for this project. One of the key points considered at the preliminary design phase when evaluating between the use of the stainless-steel option from an investment perspective, was to look at the life-cycle costs. The bridges will be permanently exposed to a potentially corrosive environment and de-icing salts in winter. The maintenance requirements for Stainless Steel structures is limited to regular pressure washing with water to clean the structure from de-icing salt accumulation as the duplex stainless-steel grades proposed for this project ensures a high corrosion resistance.

The bridges were designed to add a distinctive visual element with a clear identity to the city of Toronto without dominating the skyline of the neighborhood. The bridges present substantial curving forms within the landscape that are visually strong in a minimal, understated and elegant way, to touch the historic setting as lightly as possible. The design was focused on both structural efficiency and pleasing proportioning of the geometry. Both bridges span the rail corridors almost perpendicularly to minimize the crossing distance. Also, both bridges use trapezoidal cross sections for girders and triangular cross sections for arch ribs. To accommodate the 5m elevation difference between the ends of the South Bridge, a curved landing is proposed to gracefully connect the bridge to adjacent paths (Figure 1).

Figure 1. Aerial View render

The Design-Build Team proposed a unique Fort York arch design: a tied stainless-steel network arch with a distinctive crossing diagonal hanger pattern and a triangular cross section profile, with a single arch rib inclined at 18 degrees to provide a slender, transparent and elegant structure. The arches tilt in opposing directions for each bridge, to create a more dynamic visual experience for users. Structures that are configured differently but still retain a continuity of expression.

The structural system selected for both bridges is similar, with a slightly different geometry.

3.1 North Bridge

The bridge has a single span with total length of 52 m between the axis of the abutments (Figure 2). The arch has a parabolic elevation with a maximum rise over the deck elevation 9 m resulting in a dynamic and relatively flat rise-to-span ratio of 1:5.8 selected for aesthetics reasons.

Figure 2. View of North Bridge looking South

The hollow rib has a triangular cross-section 900 mm wide and 450 mm deep with a central web made from steel plates with thicknesses ranging between 15 and 40 mm wich eases the connection with the hangers. A triangular cross-section was selected to benefit of the effects that sunlight will create, reinforcing its visual slenderness, as well as to facilitate fabrication utilizing standard hot-rolled steel plates (Figure 3).

Figure 3. View of North Bridge from deck

The arch is connected to the tie-girder at both ends and by two families of inclined hangers that cross each other once which provide additional stiffness to the structure (Figure 4). The hangers are inclined 60 degrees to the horizontal and consist of 36 mm diameter stainless-steel rods that provide a clean a smooth appearance compared to traditional cables. This arch system is a very efficient structure; the arch works like a truss with minimum bending moments and shear forces, even for asymmetrical live loads unlike arches with vertical hangers.

Figure 4. View of hanger net

The triangulation of hangers provides restraint to the horizontal component of load due to the inclination and against buckling. Therefore, both the arch and tied-girder can have cross-sections with very slender dimensions that make the bridge more transparent and lighter. Hangers only take axial forces and work in tension. At both ends of the rods, an eye fork fitting provides length adjustment. The forks are connected to both the arch rib and the deck with steel plate gussets to create an elegant and simple pinned connection.

The steel deck system is connected with a 180 mm depth concrete slab on top. The slab is reinforced with stainless-steel rebars and acts in composite action with the box girder and ribs to take advantage of the two materials (Figure 5). The concrete deck, unlike other lighter deck systems, provides the minimum mass and a higher damping ratio required to prevent excessive vibrations that would be, otherwise, uncomfortable for users.

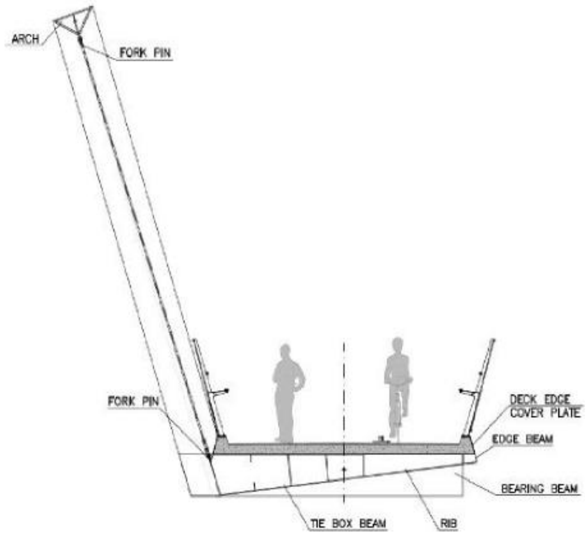

Figure 5. Typical Cross-Section

3.2 South Bridge

Unlike the North Bridge, the south crossing links the Ordnance Triangle to Fort York with a 5 m elevation difference that imposes a different bridge design concept. After assessment of various arch alternatives, the solution that best fits the site constraints is a one-span arch connected to a V-shape pier on the south end.

This unusual structural system is very efficient as it transforms the thrust of the arch into a set of axial forces in the V-pier that also provides a greater openness underneath the crossing (Figure 6).

The 49 m long bridge crosses the rail corridor with a straight alignment perpendicular to the tracks to minimize the length of the structure over the rail. The span length between the axis of the abutment and the pier axis is 44.5 m. The bridge platform extends to the south to blend with a curving approach structure oriented to the west with a projecting lookout to the East.

Figure 6. View of South Bridge

Similar to the North Bridge, the arch is inclined 18 degrees to the vertical, but here tilts towards the west to open up views towards the downtown skyline. The arch and tied-box girder features geometry similar to the one designed for the North Bridge with some adjustments of the arch width and various plate thicknesses that are adapted to its structural demand.

The South Bridge landing includes a 58 m long structural ramp on the west side terminating in a cantilevered lookout on the east side. The ramp is a continuous reinforced concrete girder with typical spans of 12 m to minimize the structure depth and provide open up views underneath. The structure is continuous with the bridge and integral with the pier to minimize future maintenance. The piers have a trapezoidal cross section and are made of reinforced concrete. The two side faces of each pier are clad in permanent weathering steel that provides a natural material contrast with the stainless-steel that helps visually ground the bridge in its heritage setting.

4 ANALYSIS AND DESIGN

The analysis has been performed using a three dimensional elastic model (Figures 7 and 8). The construction stages were considered to make the necessary checks and provide geometry and forces control during the construction phases.

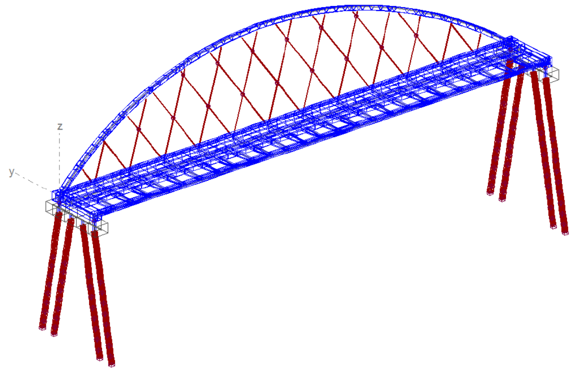

Figure 7. Analysis Model for North Bridge

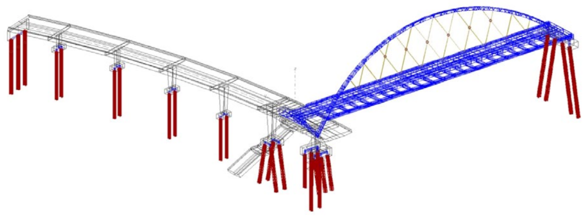

Figure 8. Analysis Model for South Bridge

The first stage is the non-composite stage which represents the state of the bridge before the in-situ concrete slab is casted. This stage is necessary to obtain the effect of the permanent loads and construction loads before the deck becomes composite. The permanent loads considered in this stage were the self-weight of the stainless-steel structure and the self-weight of the deck precast panels which have been used as a permanent formwork. Other construction loads considered in this stage were the wind for a 10 year return period event as per specified by the applicable code CAN/CSA-S06-06 and the construction live load.

During construction, two stages were studied in order to assess the stability adequacy of the structure. Instability could arise from the wind load acting on the unfinished structure. The first stage comprised the bare steel structure which including temporary safety barriers for the workers, acting as a wind parapet subjected to the 10-year return period wind. In this stage there is no contribution to the stability from the concrete deck weight. The second stage was after the installation of the deck precast panels, which increased the surface exposed to vertical wind. On the other hand, the weight of the panels was favorable to the stability. A special temporary device was designed to restrain the structure to the abutments and prevent from uplifting during the temporary stages of erection on site.

Another key aspect of the analysis during construction was to assess the correct behavior of the bridge during the stages of erection on site. Different sections of the arch and the deck were prefabricated and assembled on temporary supports on site. An analysis of the de-propping sequence of the structure was performed to verify that the deformations measured on site matched with the analytical results within a given tolerances.

The final stage during service, once the composite effect has been achieved, was divided into two loading conditions. One condition applies for the permanent loading such as the weight of the barriers or utilities which produce long-term effects. A ratio of 3 is applied to the stiffness of the concrete slab to account for the effect of creep and shrinkage as per the applicable code CAN/CSA-S6. Finally the other condition is for short-term loads such as the live loads and the wind loads.

The bridge was also checked for the ice accretion action due to the climate condition on the area, for instability due to buckling and for serviceability in terms of deflection and vibration.

In order to evaluate the susceptibility of the bridges to aeroelastic instabilities, an analysis was carried out their susceptibility to wind instability. The analysis was performed on the bare cross sections with the electrification shrouds. The possibility of the railings being opaque and blocked due to ice accretion was also considered. A sectional. Computational Fluid Dynamic, CFD, analysis, wind climate investigation, were carried out, (Figures 9, 10 and 11).

The applicability of design wind loads according to CAN CSA-S6 was also investigated. The wind analysis concluded that the design wind loads defined in the code have been properly accounted for. Moreover, the structures are stables up to a wind speed clearly higher that the Code requirement regarding vortex induced vibration, galloping, torsional divergence and flutter.

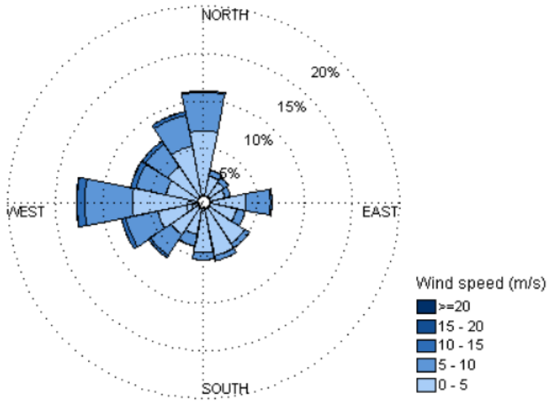

Figure 9. Windrose of 10 minutes mean wind speeds recorded ant Toronto Airport.

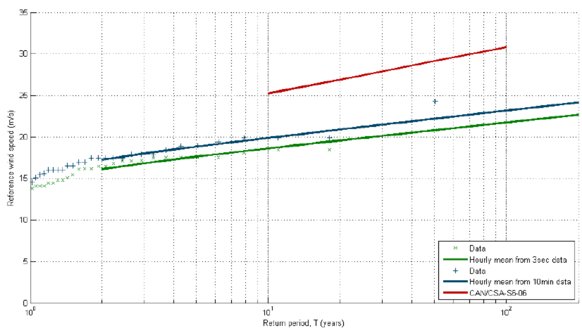

Figure 10. Extreme wind speed distribution of hourly mean wind speeds recorded at Pearson International Airport compared with CSAS-06 proposed values.

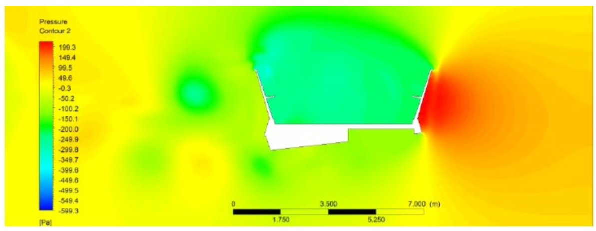

Figure 11. Pressure contour with solid handrails, CFD analysis.

A detailed dynamic analysis for the pedestrian loads was carried out. The analysis was made using two methods, the AFGC-06 [4] method including the effect of moving and time-dependent loads, see Figure 12, and the CSA-06 simplified method. In both cases the footbridges fulfilled the recommended verification criteria.

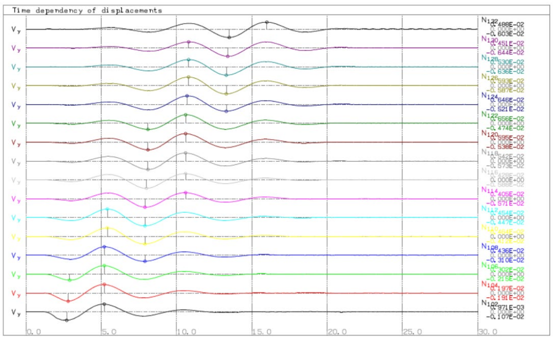

Figure 12. Analysis results. Vertical acceleration for one pedestrian time-dependent moving load.

5 CONSTRUCTION

Construction started in August 2016, the steel superstructures were installed in October 2018 and the structures finalized in early 2019. Project completion, including finishes and landscaping, is expected by June 2019.

Due to the presence of softened clayey soils, shallow spread footing foundations were not suitable for support of the pedestrian bridge abutments, and deep foundations were adopted. The deep foundation solution consists of steel H-piles, fitted with bearing points and driven into the shale. The abutment and pier pile caps have been maintained as high as possible, to minimize excavation and groundwater control requirements.

5.1 Fabrication

Fabrication and erection were carried out in accordance with the Design Guide for Structural Stainless-Steel (DG-27) of the American Institute of Steel Construction. Welding was performed in accordance to the AWS D1.6/D1.6M. Stainless-Steel is not a difficult material to work with. However, in some respects it is different from carbon steel and should be treated accordingly. It is crucial to preserve the good surface appearance of the stainless-steel surfaces throughout fabrication with simple precautions and good engineering practice

Great care is required in storing and handling stainless-steel than carbon-steel to avoid damaging the surface finish and to avoid contamination by carbon steel and iron. Stainless-steel can be cut by usual methods, but power requirements are greater than those used for carbon steel due to work hardening. Grade 2205 has excellent machining properties compared to other stainless-steels.

Duplex Stainless-Steel grade has excellent weldability and most of the typical welding methods such as SMAW, GTAW, GMAW, SAW among others can be used. The material should be welded without preheating and allowed to cool between welding passes to below 150ºC. Post-welding annealing after welding with filler is not necessary. Inspection of welds was carried out by AWS certified weld inspectors, duly experienced in welding stainless-steel. Examination methods for welds are like those used for carbon steel. Ultrasonic methods have been tested to prevent difficulties of interpretation.

In order to restore the stainless-steel surface and corrosion resistance after welding and fabrication, it is necessary to conduct a post-fabrication treatment such as pickling, brushing and blasting to remove all scale and contamination (Figures 13 and 14).

Figure 13. Steel Fabrication of arch

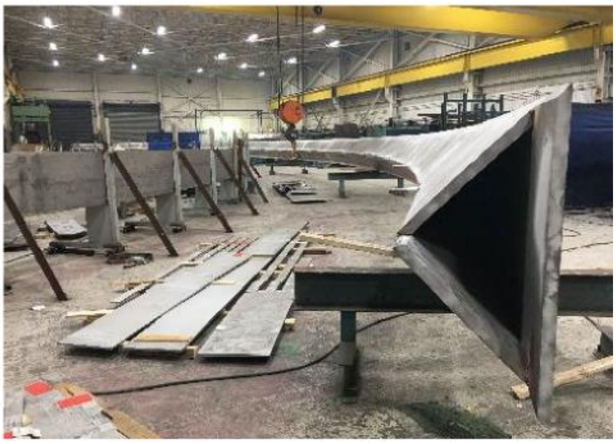

Figure 14. Steel Fabrication of box girder and deck

5.2 Erection

The construction of the bridges has its own challenges. The bridges have been conceived to minimize interference with the rail and streamline the construction time. Most of the bridge components were prefabricated at the shop and assembled at the site to accelerate construction and ensure quality. The steel parts were prefabricated in sections to facilitate transport to the site. Both the tied girder and arch were fabricated to the required camber to compensate for deflections due to all dead loads and match the design profile elevation.

All Stainless-Steel visible surfaces were bead blasted after pickling to get a consistent uniform dull finish with a natural silver colour and remove all scale and surface contamination arose from fabrication.

A key element of this strategy was to minimize the number of iterations of construction mobilization. Upon completion of access to the assembly areas, the bridges were assembled and erected on the accesses to minimize noise and disturbances to neighboring residential areas in the north and to the Fort York. Upon delivery of the sections to the site, the arch and tied-girder sections were assembled in pre-set positions on temporary supports at close intervals without hangers. The main field splices are designed for field welding for aesthetic reasons. After completion of the arch and once it is connected to the tied girder, the arch was released to take up its true shape.

Then, the hangers were installed, and hand tightened, and the intermediate supports of the tied girder removed to let the hangers take up their steel dead load tension. The 130-ton bridge superstructures were hoisted into the final position with a crane placed at one end using a 600-ton hoisting capacity crane. The lift of the two bridges was done at night in two different weekends to avoid/minimize rail traffic disruption in July and October 2018 (Figure 15).

Upon placement of the steel structure, the placement of pre-cast partial depth concrete panels over the ribs continued through the night the bridge was lifted for then pouring the top cast-in-place concrete deck slab. After this operation, the hangers take up their final permanent load tension. The bridges will be completed with the finishes, including the illumination system.

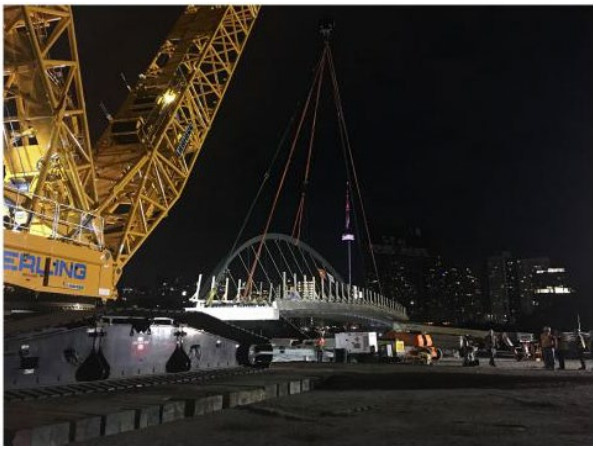

Figure 15. North Bridge Lifting

The Footbridges have already been opened to traffic in October 2019 (Figures 16 and 17).

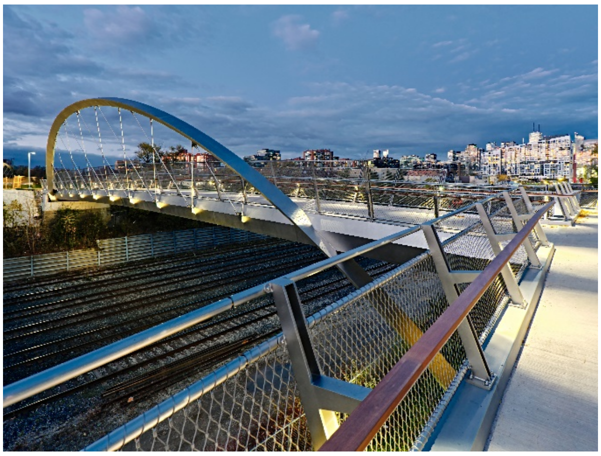

Figure 16. South Bridge from South Access. Night view.

Figure 17. South Bridge from North Access.

6 CONCLUSIONS

The Garrison Crossing Pedestrian and Cycle Bridge Project includes a unique arch design: a tied stainless-steel network arch with a distinctive crossing diagonal hanger pattern and a triangular cross section profile, with a single arch rib inclined at 18 degrees to provide a slender, transparent and elegant structure, that is easy to build, with an extended lifecycle and little maintenance required. The proposed design in stainless-steel was awarded within a design and build project context competing against other bridge alternatives using carbon steel.

The design has been driven by utilizing less material and energy, providing an extended life span and easy maintenance even if the initial cost is slightly higher. The use of Stainless Steel represents a net advantage for the Owner in terms of minimizing their maintenance, in addition to improving safety and long-term durability.

One of the key points to consider when evaluating between the carbon and stainless-steel option from an investment perspective, is to look at the lifecycle costs which includes all anticipated maintenance costs. Stainless-steel is particularly beneficial for structures with significant maintenance constraints such as bridges over railway or water as it will eliminate the need of major associated costs (workers protection, flagging, etc.) and indirect cost used to the users during repair proceedings.

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