IOP Conf. Series: Materials Science and Engineering **419** (2018) 012005 doi:10.1088/1757-899X/419/1/012005

Lightweight solution for existing steel movable bridge retrofit and repair

Antonella Ruzzante[1], Roberto Pavan[1]

[1]AP&P srl, Minadois Str. 20, Rovigo 45100, Italy

E-mail: info@pipinatoandpartners.it

Abstract. Prolonging the life of existing steel movable bridges is a paramount problem for managing authorities, where these specific types of bridges have reached a prolonged state of use. The unsatisfactory behaviour of these structures under the current type and increasing number of loads make clearer that innovative solutions are needed. For this purpose, the realization of lightweight composite decks is needed, in order to redistribute the common actual load onto a structure conceived with historical codes, characterized by lower design live loads. The possibilities of retrofitting bridges with this solution studied in a recent research program are presented and compared in this study.

1. Introduction

The increasing traffic density and vehicle weight have been clearly noted worldwide in recent decades. Many existing movable bridges, all over the world, were not designed for the high service loads and the increased number of load cycles that they are exposed to today. Some bridges will have to be either strengthened or replaced in the next decades. Movable bridges have proved to be an economical solution to the problem of how to carry a rail line or highway across an active waterway. A "closed" movable bridge has closed the waterway to marine traffic, while an "open" bridge has opened the water-way to marine traffic. Highway bridges are typically de-signed to remain in the closed position and only to be opened when required by marine traffic. However, movable railroad bridges can be designed to remain in either the open or closed position, depending on how frequently they are used by train traffic. The difference is important as different wind and seismic load design conditions are used to design for a bridge that is usually open vs. one that is usually closed. The three major categories of movable bridges are swing, bascule, and vertical lift. This list is not exclusive and there are other types, such as jackknife, reticulated, retracting, and floating that are not common and will not be described here. Movable bridges are designed to be operated following a set protocol, and this protocol is incorporated into the control system as a series of permissive inter-locks. The normal sequence of operation is as follows. Vessel signals for an opening, usually through a marine radio but it can be through a horn. For a highway bridge the operator sounds a horn, activates the traffic signals, halting traffic, lowers the roadway gates, then lowers the barrier gates. For a rail bridge the operator needs to get a permissive signal from the train dispatcher. After the barrier gates are lowered, a permissive signal allows the operator to withdraw the locks and/or wedges and lifts and, once that is completed, to open the span. The vessel then can proceed through the opening. To close the bridge, the steps are reversed. The controls are operated from a control desk and Note that the control desk includes a position indicator to demonstrate the movable span(s) position as well as an array of push buttons to control the operation. A general objective in designing such a desk is to have the position of the buttons mimic the sequence of operations. Typically, the but-tons are lit to indicate their status. or every type of movable bridge there are a wide amount of interventions needed both every year, both during long time scheduling maintenance. The most frequent interventions lie on the moving equipment maintenance and checks, while the structural maintenance and eventual retrofit refers to longer period.

Figure 1: In service movable bridge.

2. Retrofit solutions: literature survey

A special category of steel structures where the fatigue induced damage is relevant for the life cycle of the structure, deals with movable bridges. These are daily subjected to high level stresses induced by load cycles of passing vehicles: the incrementing speeds and concurring dynamic amplifications, and the incremental number of loads and number of vehicles, represented a critical structural situation especially for those bridges in principle lines and with some decades of exercise. The literature for these detailed analysis and damage assessment is not so extensive, and relegated to a small number of specialists: guidelines for the assessment of historical existing steel structures are deepen in Kuhn et al. (2008) and Brühwiler et al. (2012), in a sort of pre normative design document, respectively in the European and Swiss context; while well-established authorities in this framework have studied riveted bridges Fisher et al. (1984), Brühwiler et al. (1990), other studies are focused on large scale experimentations and damage assessment procedures (Pipinato et al 2008b; Pipinato et al. 2009; Pipinato et al. 2010a; Pipinato et al 2011c; Pipinato 2011; Pipinato 2012a); a detailed procedures for accounting for remaining fatigue life is provided in Imam et al. (2005), while other studies are more focused on the structural analysis of single bridges (Pipinato et al. 2012a; Pipinato et al. 2012a; Pipinato 2010b; Pipinato et al. 2012e; Pipinato et al. 2010a; Pipinato and Modena 2010 Pipinato et al. 2008) even considering special combination of external loadings, and damage accumulation including fatigue and seismic loads (Pipinato 2012b); or FRP interventions for build up new structures or repairing solutions Pipinato (2012d); particular cases of damages are included also in some hint studies (Pipinato et al. 2012e; Pipinato et al. 2012c) re-porting particular analysis solutions that can help to solve bridge damaged systems; retrofit procedures and load analysis also for high speed bridges are reported in (Pipinato 2013a,b,c), also coupling damage as in the aforementioned studies (Pipinato 2012c; Pipinato et al 2011a; Pipinato et al 2010b) a particular subset of these studies includes damage analysis and control of existing and historical bridges (Pipinato 2012d; Pipinato et al.

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2013); reliability analysis also considering dynamic effects are described in (Imam et al. 2012; Imam et al. 2012; Kaliyaperumal et al. 2011; Imam and Righiniotis 2010), while a more focused study on the probabilistic fatigue evaluation of riveted bridges is included in Imam et al (2008); the fatigue analysis of riveted bridge connections using the theory of critical distances and relative numerical modelling are described in (Righiniotis et al. 2008; Imam et al. 2007); while a general introduction on the specific argument could be found in (Imam et al. 2006; Imam et al. 2005); more focused and specialist deepens deals with the fracture reliability of a typical Northridge steel moment resisting connection (Righiniotis and Imam 2004), the fatigue reliability of riveted connections in bridges (Imam et al. 2006, 2008), the ef-fect of climate change on the deterioration of steel bridges (Kallias and Imam 2013), the risk assessment of steel bridges under the influence of changing environ-mental conditions (Kallias and Imam 2012), the fatigue assessment of a bridge detail using dynamic analysis and probabilistic fracture mechanics (Imam and Kaliyaperumal 2012), the modelling of failure consequences for robustness evaluation (Chryssanthopoulos et al. 2011), the review of metallic bridge failure statistics (Imam and Chryssanthopoulos 2010), the effects on the fatigue reliability of deteriorating riveted bridges (Imam et al. 2009a), the global-local finite element analysis of riveted bridge connections for fatigue evaluation (Imam et al. 2009b), the probabilistic fatigue load spectra for riveted bridges (Imam et al. 2007), the probabilistic fatigue life estimates for riveted bridges (Imam et al. 2006), the effect of fracture on the reliability of a moment resisting frame under earthquake loading (Righiniotis and Imam 2006), the probabilistic fatigue life estimates for riveted bridges (Imam et al. 2006), the remaining fatigue life estimates for riveted bridges (Imam et al. 2005), and the connection fixity effects on stress histories in riveted rail bridges (Imam et al. 2004).

3. Movable bridge deck intervention

A special As a fact, the most damaged structure of movable bridges is represented by the deck. A crucial part of the design of movable bridges is to limit the moving dead load which affects the size of the counterweight, the overall size of the main structural members, and, to a lesser extent, the machinery depending upon the type of movable bridge. For movable railroad bridges this is typically not a problem, as movable span decks are de-signed with open decks (timber ties on stringers) and the design live load is such a large part of the overall de-sign load that the type of deck is not an issue. For high-way bridges, however, the type of deck needs to be carefully selected to provide a minimum weight while providing an acceptable riding surface. Early movable spans used timber decks, but they are relatively heavy and have poor traction and wear. Timber was replaced by open steel grid, a good solution that is both light-weight and long wearing. In addition, the open grid reduced the exposed wind area, particularly for bascule bridges in the open position. However, with higher driving speeds, changes in tires and greater congestion, steel grid deck has become the source of accidents, particularly when wet or icy. Now most new movable bridge decks are designed with some type of solid sur-face. Depending on the bridge, this can be a steel grid partially filled with concrete or epoxy, an orthotopic deck, lightweight concrete, or the “exodermic” system. Aluminum and composite decks are also now being developed and may prove to be a good solution. While orthotropic decks would seem to be a good solution, as the deck can be used as part of the overall structural system, they have not yet seen widespread use in new designs.

Consequently, a number of factors that should be considered in the selection of a lightweight solid deck system to replace steel open grid deck on typical movable bridges. These factors include (URS 2012):

- Costs including:
  - o Deck fabrication and installation,
  - o Modifications to the bascule leaf steel framing, bascule pier, flanking spans, counterweight, and trunnion assemblies required to implement the new deck system,
  - o Design and construction inspection for the new deck system,
  - o Future maintenance and inspection.
- Functionality and Safety including:

o Load capacity (i.e. support of legal loads and permit-ted overloads),
o Improved riding surface and skid resistance for vehicular and bicycle traffic,
o Reduced traffic generated noise.
- Maintenance including:
o Ease of repair and/or replacement of all or portions of the deck,
o Need for periodic maintenance (e.g. reapplication of coatings and/or replacement of wearing surfaces).
- Service-life and Durability including:
o Deck and/or deck component (e.g. wearing service, fasteners, etc.) service-life,
o Resistance to corrosion, fatigue, wear, impact, fire, ultraviolet light, and chemicals,
o Accommodation of thermal movements.
- Constructability including:
o Disruption to traffic (e.g. overall construction duration, maintenance of traffic),
Ability to accommodate fabrication and installation tolerances,
o Sensitivity to environmental conditions during construction,
o Shipping, storage and handling,
o Specialized inspection requirements during fabrication and installation.
- Other Risks including:
o Familiarity of the product and technology (e.g. years' experience, previous bridge installations, quantity and quality of applicable research, endorsement by bridge design community),
o Availability of design tools and construction techniques,
o Financial and technical support from supplier(s),
o Product availability (e.g. opportunities for competitive bidding, sole source and/or patents).

These new lightweight solid decks to replace steel open grid decks on typical movable bridges include:
a) Sandwich Plate System
The Sandwich Plate System is a proprietary and patented composite laminate plate material consisting of thin metal faceplates continuously bonded to a polyurethane elastomer core. The elastomer core transfers forces between the metal faceplates by way of shear, analogous to an I-beam when subjected to flexure with the steel plates acting as the flanges and the elastomer core as the web. The elastomer core also prevents local buckling of the metal faceplates in compression, which permits development of full yield of the metal face-plates. Panels are very thin (1 to 2 inches thick) com-pared to traditional bridge decks. The use of these thin panels is possible through a combination of panel bending and membrane action (i.e. in-plane tension). Separation of the thin metal plates with a lightweight elastomer core more efficiently increases strength and stiffness of the plate, while minimizing the increase in weight of the plate (URS 2012).
b) Aluminum Orthotropic Deck
Aluminum alloys have much to offer for bridge deck applications, and continue to be used, primarily over-seas, where their lightweight, high strength-to-weight ratio and excellent corrosion resistance satisfy service requirements. Aluminum is manufactured by an extrusion process, which permits highly customized sections that can be optimized for a given application. The lack of widespread use of aluminum, despite the structural and maintenance advantages, is primarily due to the high initial cost of the material (URS 2012).
c) Fiber Reinforced Polymer (FRP) Composite Deck
Fiberglass reinforced plastic (FRP) is a composite material that has a number of characteristics that makes it a good alternative to replace steel open grid deck on bascule bridges. FRP composites can be designed to pro-vide a wide range of mechanical properties including tensile, flexural, impact and compressive strengths. FRP composites are generally lightweight (i.e. approximately 20% of steel) with high strength-to-weight ratio and are generally resistant to creep and fatigue. FRP composites are versatile and can be fabricated in many different configurations, customized specifically for a given application (e.g. bridge decks), designed and fabricated such that the strength is oriented to meet specific configuration and loading demands, made into larger more complex structural components and systems that simplifies connections and minimizes the number of components that

must be handled. The relatively low modulus of elasticity of FRP composites make them relatively flexible compared to other bridge deck materials and thus deflections generally control the design of FRP bridge decks. FRP composite materials are susceptible to degradation from ultraviolet light and chemicals; however, the materials can be formulated with additives to improve the resistance to these effects (URS 2012).

d) Ultra-high Performance Concrete (UHPC) thin deck

Ultra-High Performance Concrete (UHPC) is a material that has recently gained attention in the bridge industry. UHPC provides a combination of superior properties including strength, ductility, durability that permits design and construction of thinner sections and longer spans that are lighter and more efficient, while providing improved durability and impermeability against corrosion, abrasion and impact. UHPC has potential to be used in an alternative deck design to replace steel open grid deck. The high concrete compressive and tensile strength allows design and construction of a lightweight waffle slab bridge deck with thin elements (slab and ribs) (URS 2012).

e) Making composite existing non-composite decks

Many older steel bridges are constructed with a non-composite concrete slab over steel girders. A potentially economical means of strengthening these floor systems is to connect the existing concrete slab and steel girders to permit the development of composite action. Composite action means that the steel girder and concrete can help each other out carrying the loads more efficiently than in the original nanocomposite condition. To achieve the benefits of composite action, the existing steel girder must be connected to the existing concrete slab to permit the transfer of shear forces at the steel-concrete interface.

4. Conclusion

Many existing movable bridges, all over the world, were not designed for the high service loads and the in-creased number of load cycles that they are exposed to today. Some bridges will have to be either strengthened or replaced in the next decades. For this reason, in this paper specific intervention are presented, including the following: bridge deck traditional intervention; light deck intervention (including SPS systems, aluminium orthotropic deck, FRP composite deck UHPC thin deck, making composite existing non composite solutions). According to the specific situation, span, loads, traffic, service life to be maintained, the proper solution or a combination thereof should be designed.

Acknowledgments

This research was supported by the European Union, represented by the European Commission Di-rectorate General for Research and Innovation, Research Fund for Coal & Steel (RFCS) program, under grant agreement no. RFSR-CT-2015-00025. This funding is gratefully acknowledged.

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