100-Year Performance of Timber–Concrete Composite Bridges in the United States

James P. Wacker, M.ASCE[1]; Alfredo M. P. G. Dias[2]; and Travis K. Hosteng, M.ASCE[3]

Abstract: The use of timber–concrete composite (TCC) bridges in the United States dates back to approximately 1924 when the first bridge was constructed. Since then a large number of bridges have been built, of which more than 1,400 remain in service. The oldest bridges still in service are now more than 84 years old and predominately consist of two different TCC systems. The first system is a slab-type system that includes a longitudinal nail-laminated deck composite with a concrete deck top layer. The second system is a stringer system that includes either sawn timber or glulam stringers supporting a concrete deck top layer. The records indicate that most of the TCC highway bridges were constructed during the period of 1930–1960. The study presented in this paper discusses the experience and performance of these bridge systems in the US. The analysis is based on a review of the relevant literature and databases complemented with field inspections conducted within various research projects. Along with this review, a historical overview of the codes and guidelines available for the design of TCC bridges in the US is also included. The analysis undertaken showed that TCC bridges are an effective and durable design alternative for highway bridges once they have shown a high performance level, in some situations after more than 80 years in service with a low maintenance level. **DOI: 10.1061/(ASCE)BE.1943-5592.0001513.** *© 2020 American Society of Civil Engineers.*

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Introduction

The first references to timber–concrete composite (TCC) bridge decks in the United States date from the early 1920s. The interest began in the Northwest, leading to cooperation between the City of Seattle and the University of Washington, aiming to combine the wear resistance of concrete with the low cost of timber (DELDOT 2000). From this initiative resulted what is believed to be the first timber–concrete composite bridge constructed with a T-section as early as 1924.

In the following decade, J. F. Seiler proposed and patented ["Composite Wood and Concrete Construction," US Patent No. 2,022,693 (1993)] a timber nail-laminated deck approach for TCC decks. The proposal was based on experiments developed in collaboration with the engineering laboratory of George Washington University in Washington, DC. This approach was used in different locations of the United States, including Delaware, Florida, and California (DELDOT 2000; van der Linden 1999).

Later, Conde B. McCullough, assistant chief engineer at the Oregon State Highway Department, presented the results of a series of experimental tests, whose aim was the development of composite T-sections. Various configurations and connection systems were analyzed in the work that was republished in 1943 (McCullough 1943). The author mentions that based on the results from these tests more than 180 structures with a total cumulative length of more than 3.79 mi had been built at that time.

In the late 1940s and early 1950s, a large number of timber stringer bridges were rehabilitated with a concrete deck overlay. A good example of this are the 127 timber bridges originally built in the late 1920s and early 1930s along Historic Route 66 (National Trails Highway) between the cities of Barstow and Needles in California, an approximately 257.5 km (160-mi) corridor. Most of these bridges are still in service but many have vehicle load restrictions due to their damaged or deteriorated members, mostly timber members but Xalso concrete members (Lardner & Klein 2015). In the early 1950s a publication on the TIM-PRESS described a new timber–concrete composite solution for bridges, in this case based on glued laminated timber stringers, for spans up to 30.5 m (100 ft) (TIM-PRESS 1953). Records indicated that at the time 20 of these bridges had been built and another 10 were to be constructed in the near future.

There are other mentions to more recent construction of TCC bridges, such as one built in Sussex County, Delaware, in 1984 (DELDOT 2000), or another one built in Fairfield, Maine, based on a research project undertaken by the University of Maine (Weaver et al. 2004), as well as to research projects in which new technologies have been proposed (Balogh et al. 2008; Yeoh et al. 2013; Gutkowski et al. 2008; Fragiacomo et al. 2007).

In contrast to what has occurred in recent times (Rodrigues et al. 2013) when research studies motivated pilot timber–concrete bridges, these early research studies were motivated by the practice of looking for validation and optimization of the solutions already being built (Baldock and McCullough 1933; Richart and Williams 1943). Another important difference in early times was that the motivation to use this structural solution was mostly for economic reasons due to steel's higher cost during the Great Depression of the 1930s and its scarcity during the war efforts of the 1940s (WPN 1941; McCullough 1943), while nowadays additional factors such as sustainability are also relevant (Rodrigues et al. 2017; Yeoh et al. 2011).

The application of this solution in new and rehabilitation-type projects of timber bridges has been widespread in the US since the

[1]Research Engineer, Forest Products Laboratory, One Gifford Pinchot Dr., Madison, WI 53726. Email: jwacker@fs.fed.us

[2]Assistant Professor, Dept. of Civil Engineering, Univ. of Coimbra, Campus II, Rua Luis Reis Santos, Coimbra 3030-788, Portugal (corresponding author). ORCID: https://orcid.org/0000-0002-9752-1907. Email: alfgdias@dec.uc.pt

[3]Director/Engineer, National Center for Wood Transportation Structures, 2711 S. Loop Dr., Ames, IA 50010. Email: kickhos@iastate.edu

Note. This manuscript was submitted on January 29, 2019; approved on August 7, 2019; published online on January 16, 2020. Discussion period open until June 16, 2020; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Bridge Engineering***, © ASCE, ISSN 1084-0702.

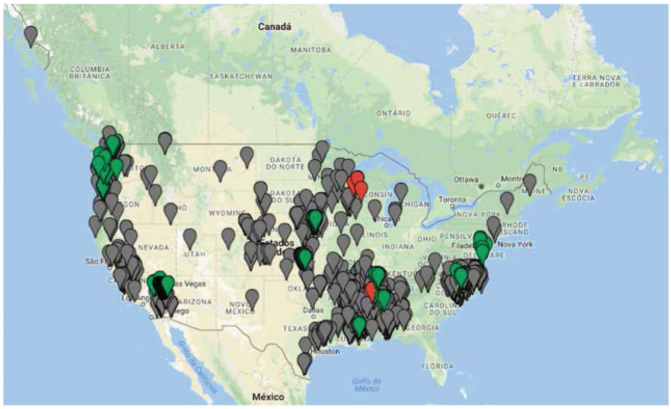

Fig. 1. (Color) Location of the timber–concrete composite highway bridges in the United States as reported in NBI (FHWA 2016). Green = confirmed; red = not confirmed; and gray = no information based on available inspection reports. (Map data © 2016 Google, INEGI.)

early 1920s. This experience gives a unique field for the analysis of the performance of timber–concrete bridges in both the short and long terms. In this paper, the reality in terms of use of timber–concrete bridges in the US is analyzed. Additionally, the assessment of its short- and long-term performance will be discussed based on the available data, either from reports and publications available in the literature or from field inspections that were carried out in a recent research project initiated in the USDA Forest Products Laboratory (FPL) in close collaboration with Iowa State University and the University of Coimbra in Portugal.

Use of Timber–Concrete Bridges in the US

A wide range of information regarding timber–concrete bridges in US is available through the US National Bridge Inventory (NBI) (FHWA 2016), a comprehensive database of in-service bridge information first established in the 1970s to establish new inspection requirements and improve bridge safety. From the whole set of more than 116 parameters collected for each bridge structure in the NBI, only a subsample was considered in this analysis as follows:

- Construction decade;
- Deck, superstructure, and substructure condition;
- Design load;
- Expected traffic;
- Location;
- Maximum span length;
- Number of spans;
- Total bridge length; and
- Use situation.

These parameters aimed to identify data that could provide, either directly or indirectly, information on the key focus of this work: technological solutions used, performance issues (e.g., durability, deformation, and fatigue), or evolution of the uses and solutions over time.

The US NBI reports the existence of timber–concrete bridges in 36 of the 48 states in the contiguous United States (CONUS) with some concentration on the East and West Coasts. The distribution in the map of the reported TCC bridges is given in Fig. 1, which clearly demonstrates their distribution all over the CONUS. This wide distribution within all CONUS regions is likely due to the initial construction of a new road transportation network in the US.

These bridges were built after the 1920s with a concentration in the period between World War I and World War II and immediately afterward (1920–1950). Fig. 2 illustrates the number of bridges constructed by decade. This was probably motivated by the war effort during the 1930s and road renovation after World War II during the 1950s. After this period other technical solutions such as the one based on concrete became more popular.

In the NBI, construction of this bridge type was reported before 1920; however, no other information could be found about these bridges. Some of these bridges are located at Rockford, Illinois, and one of them was constructed in 1901 [Fig. 3(a)]; however, the actual field inspection identified an old timber sawn stringer-type bridge that was widened with a concrete deck extension, which

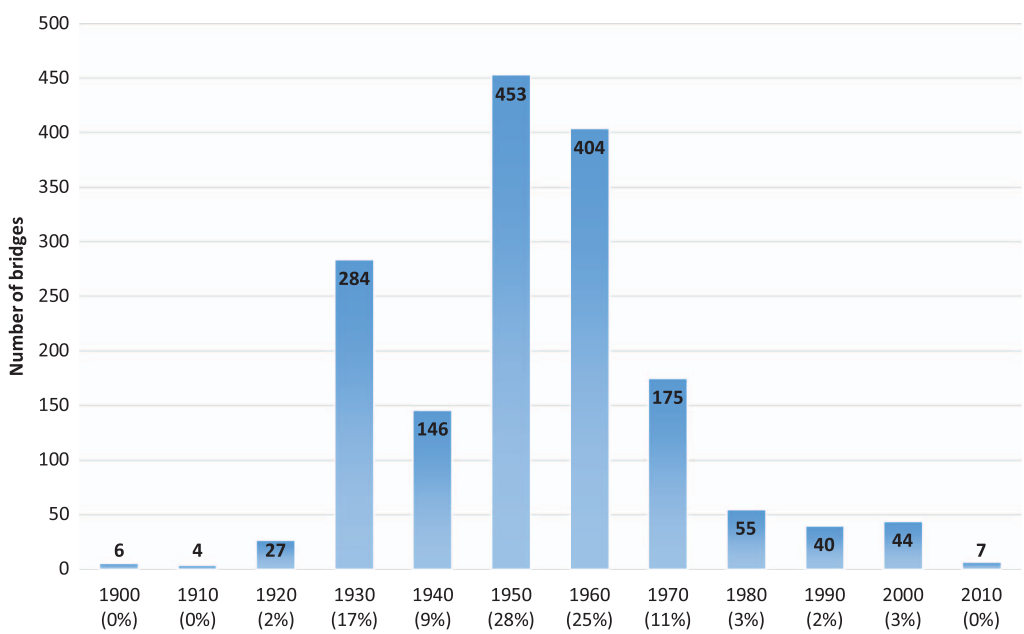

Fig. 2. (Color) Decade of construction of the TCC bridges still in service as reported in the NBI (FHWA 2016).

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Fig. 3. (Color) (a) Bridge built in 1901 in Illinois; and (b) bridge where new concrete members were added to an original timber beam bridge. (Images by Alfredo M. P. G. Dias.)

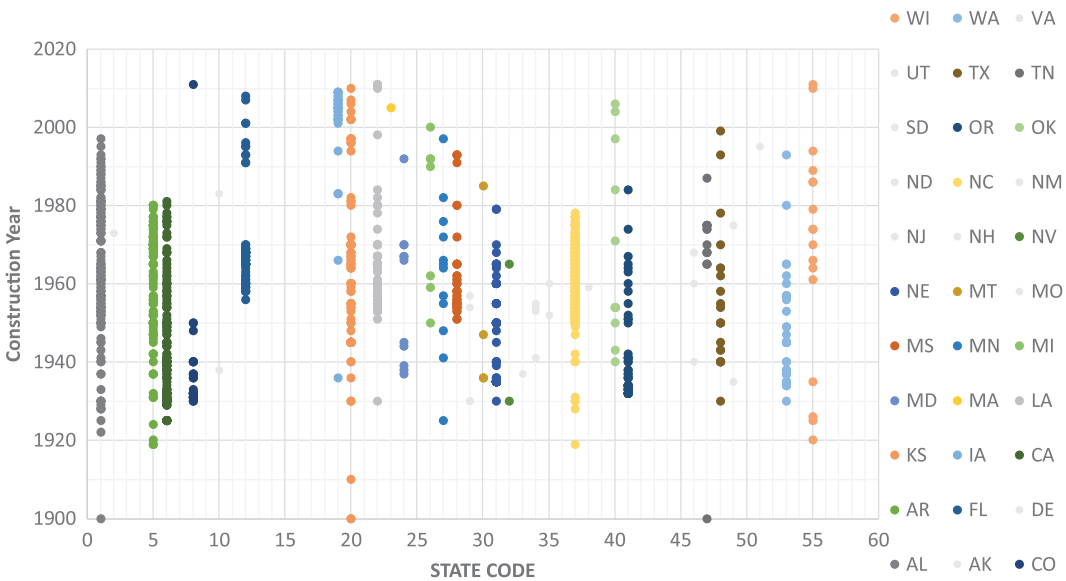

Fig. 4. (Color) Bridges by location and construction decade in 33 of the 50 states of the United States.

probably led to its ambiguities within the data included in the NBI (original construction, later addition of concrete extension).

Similar NBI data ambiguities are found in other locations such as Wisconsin or Washington State where the addition of concrete components was used in conjunction with an existing timber bridge. This type of widened bridge was incorrectly coded in the NBI as a timber girder bridge with a concrete deck [Fig. 3(b)]. This indicates that the actual number of timber–concrete bridges still remaining in service is likely less than the 1,645 included in the current NBI data sets. In Fig. 4, the quantity of TCC bridges is plotted by the state and decade (date of construction).

The graph in Fig. 4 clearly shows that the wide range of construction of TCC bridges throughout the CONUS began around 1930. After the 1970s, their use diminished sharply. However, a handful of states continued to construct new timber–concrete bridges after the year 2000.

Technical Solutions

From the start, timber–concrete bridges provided two alternative technical solutions for the superstructure: (1) slab-type deck system; and (2) T-deck. For the slab-type deck system, a longitudinal nail-laminated timber deck was assembled through the use of spikes or bolts (Seiler 1933b). Seiler promoted this new bridge system within the framework of his related US patent. The connection system used was always composed of varied depth adjacent lumber laminations combined with triangular-shaped metal plates (Seiler 1933a).

Despite it being a patented system, there are numerous reports suggesting that it was widely used, mostly on the East Coast of the United States (WPN 1938). Many of these bridges were built in high-demand locations as the Tampa–Clearwater bridges in Florida (Seiler 1934). Some of these bridges are still in service as is shown in bridge reports (DELDOT 2000) and remain in the NBI database.

The T-deck system was likely developed as a way to reinforce existing timber beams built with solid stringers and timber floors (AWPA 1941). The connection systems used in this case were more numerous and included steel fasteners, notches, and steel fasteners combined with notches (Richart and Williams 1943; McCullough 1943). Glued connections were also tested at the research level; however, no evidence from their use in practice could be found (Richart and Williams 1943). Since the T-deck was not a patented system, it likely attracted more attention and practical interest than

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Fig. 5. (Color) T-deck glued laminated bridge in Gifford Pinchot National Forest (Salmon River Bridge). (Images by Alfredo M. P. G. Dias.)

Fig. 6. (Color) (a) Chehalis River overflow road bridge in Washington; and (b) Milwaukee Street pedestrian bridge in Wisconsin. (Images by Alfredo M. P. G. Dias.)

the slab-type deck system alternative. Subsequently, a significant development began following the use of glued laminated timber members (TSI 1958), which allowed larger spans and a wide range of new possibilities not attainable with solid timber stringers. Examples of such bridges are the White Salmon River Bridge and Cascade Creek in the Gifford Pinchot National Forest in Washington State (Fig. 5). These bridges had similar detailing with a concrete deck connected to three glued laminated timber members.

In the following decades, other design configurations were adopted not only for road bridges but also for pedestrian bridges (Fig. 6). A good example of these bridges is the multispan road bridge in Chehalis, Washington, with a total length of 116.1 m (381 ft).

In spite of the introduction of new technologies, 73% of the bridges (Fig. 7) have relatively small maximum spans, between 4.9 m (16 ft) and 9.8 m (32 ft); in addition, a large number of bridges appeared to have standard span lengths [15 ft (approximately 4.6 m), 17 ft (approximately 5.2 m), and 19 ft (approximately 5.8 m)], probably resulting from the same design being replicated for these bridges.

Longer (trestle-type) bridges have been built through multispan bridges, with most having between two and four simply supported spans with total bridge lengths between 20 and 50 m (Fig. 8).

Codes and Regulations

The TCC structural solution led to its inclusion in the AASHTO highway bridge design codes. It was adopted as early as 1949 (AASHTO 1949) and guidelines specific for timber–concrete bridges are still included in the most recent editions.

5th Standard Specifications for Highway Bridges

This issue is covered in Section 9, "Composite Beams," of AASHTO (1949), where the most important design issues are discussed. The code assumes full composite interaction between timber and concrete; therefore, the calculations can be made based on an equivalent section. Indications are also given for the determination of the effective flange width for systems with both single-side and double-side flanges.

Indications for the stress calculation for beams both with and without temporary intermediate supports during the placement of the permanent dead load are given. The determination of the shear in the interface is indicated, again based on full composite interaction between the two materials. Furthermore, it is explicitly stated that the flange of the composite beam shall not be considered effective in computing the resistance to vertical shear and diagonal tension.

Some guidelines are also given for shear devices, noting that they shall allow a good concrete compaction and prevent a vertical separation between the two materials.

Standard Specifications for Highway Bridges 1983

In the 1983 edition of the AASHTO code (AASHTO 1983), there are no indications given on the model analysis; the emphasis is

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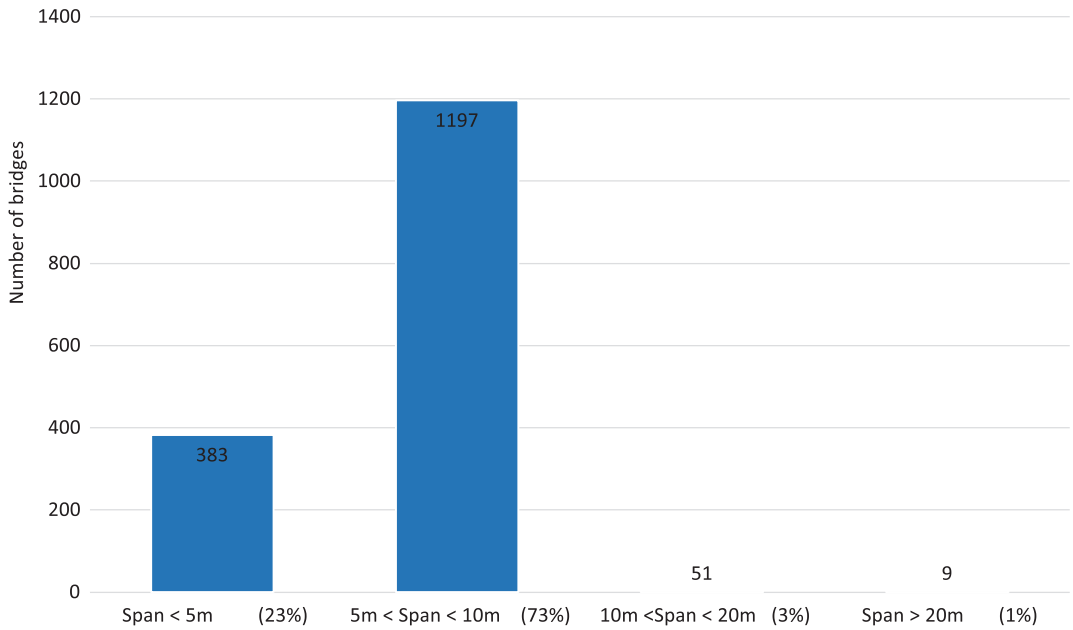

Fig. 7. (Color) Maximum bridge span according to the records from the NBI.

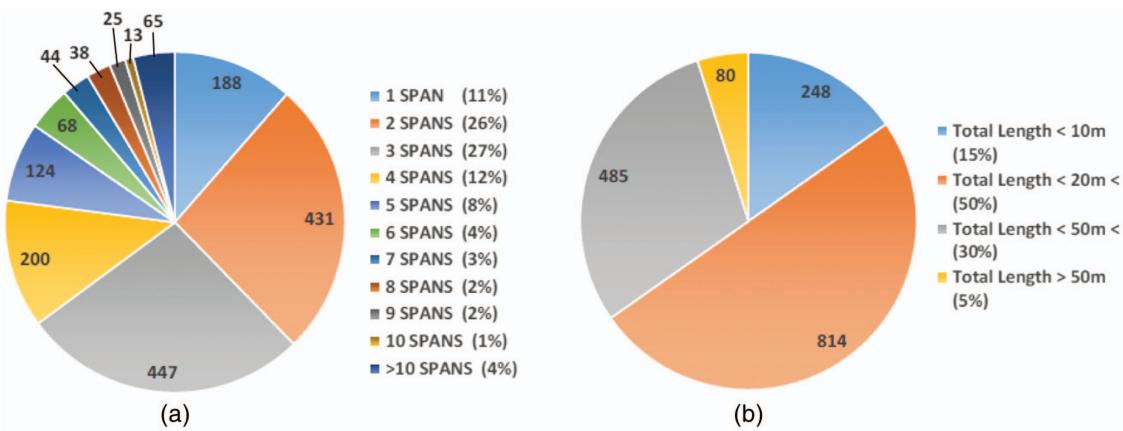

Fig. 8. (Color) (a) Number of bridge spans; and (b) total bridge span according to the records from the NBI.

instead placed on pertinent design issues critical for timber–concrete composite bridges. The 1983 edition indicates the distribution of the concentrated loads for bending and shear in both TCC slab decks and multistringer systems. Additionally, it is indicated that the (dynamic) impact loads shall be considered in computing stresses for steel and concrete but neglected for wood.

Ratios between the materials Young's modulus of elasticity are also given for use in the linear-elastic analysis of the composite systems.

It is also indicated that in composite wood–concrete decks the shear connection must resist all the horizontal shear and be made to prevent the separation between the two materials. Different connection arrangements are allowed, such as nails or grooves.

LRFD Bridge Construction Specifications

In the recent AASHTO LRFD edition (AASHTO 2014), the only indication specific for the design of timber–concrete bridges are guidelines for the lateral load distribution factors in cast-in-place concrete decks on longitudinal wood beams. The design is assumed to be performed with adequate models, such as the γ-method indicated in Eurocode 5 (CEN 2004).

Assessment of Timber–Concrete Bridges Performance in the United States

As mentioned previously, TCC bridges have a relatively long service history in the United States. As previously discussed, this type of bridge has been widely used in various environments and applications and using different technologies. For these reasons the bridges in service for a long time constitute an excellent source of information regarding the performance of in situ TCC bridges. The assessment of their performance is based on three sources of information: the NBI, inspection reports available in the literature, and field inspections performed by the authors.

The most important data from the NBI regarding the performance of bridges are their condition ratings, which are based on the required 2-year interval field inspections of each bridge. Presented in Fig. 9 are condition ratings for TCC bridges in the deck,

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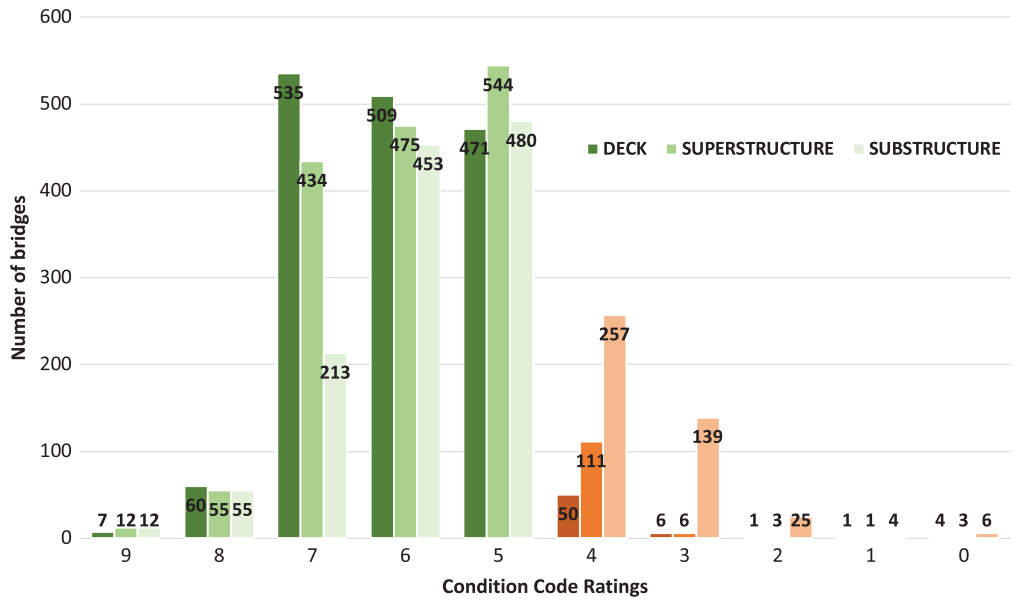

Fig. 9. (Color) Bridge condition ratings according to the NBI (FHWA 2016). The orange condition ratings indicate those conditions deemed poor or worse in the NBI ratings system.

Table 1. NBI (FHWA 2016) condition ratings

Rating	Condition
9	Excellent condition
8	Very good condition
7	Good condition
6	Satisfactory condition
5	Fair condition
4	Poor condition
3	Serious condition
2	Critical condition
1	Imminent failure condition
0	Failed condition

superstructure, and substructure categories for the bridges as reported in the NBI corresponding to condition ratings indicated in Table 1.

Fig. 9 indicates that the large majority of TCC bridges are in relatively good condition, especially considering that many have been in service for more than 50 years and up to 84 years. This is strong evidence that this bridge solution is durable and suitable for a long service life.

Such data provide valuable information regarding the general condition and performance of the bridges; however, more detailed information is required in order to have a deeper insight. Such detail can only be obtained via a thorough review of the bridge inspection reports. A total of 142 inspection reports for timber–concrete bridges identified as TCC in the NBI were subsequently located. Table 2 gives the sources of the bridge inspection reports available for this study.

The information obtained was available from five sources: (1) San Bernardino County (SBC 2016), (2) the National Timber Bridge Inspection Study (Wacker et al. 2014), (3) Maryland Historical Trust (MHT 2001), (4) field inspections undertaken in this study in 2016, and (5) field inspections undertaken in this study in 2017.

In San Bernardino County, a large number of bridge inspections were performed on TCC bridges located on Historic Route 66.

Table 2. TCC inspection database

Source	No. of reports	Construction years
US 66	58	1929–1931
National Timber Bridge Inspection Study	18	1935–1997
Maryland Historical Trust	5	1937–1945
Field inspections 2016	17	1930–1993
Field inspections 2017	44	1930–2007

A total of 133 timber–concrete bridges were identified, and recent bridge inspection reports became available for 58 bridges that were performed by Caltrans (2016). These bridges were all from the same period, 1929 and 1930; the composite solution was a way to reinforce the original timber bridges due to the need for carrying higher loads in the early 1930s (Caltrans 2016). All these are very similar bridges with standard maximum spans and designs in general. The length of the bridges was in practice defined by the number of spans once the maximum span was identified.

In cooperation with several partners (Wacker et al. 2014), FPL recently initiated a research project on the condition of US timber bridges. In this study a total of 132 timber bridges of various design types were inspected, of which 18 were actual timber–concrete composite bridges. These bridges were built in completely different periods from 1935 to 1997. These bridges were all T-section with either solid stringers or glued laminated stringers.

Another research project specific for timber–concrete composite bridges was undertaken in 2016 and 2017; within this initiative 61 field inspections were undertaken, 17 in Washington and Oregon in 2016 and another 44 in Kansas and Nebraska in 2017. The inspected bridges were selected to be representative from the existing timber–concrete bridges in terms of traffic demand, technical solutions, and age of construction. These bridges were constructed from 1930 to 1986. The inspected bridges include very old structures made with solid timber stringers up to modern glued laminated timber–concrete decks. There were also bridges along gravel roadways with less than 100 vehicles crossing each day (e.g., White Salmon River Bridge in Gifford Pinchot National

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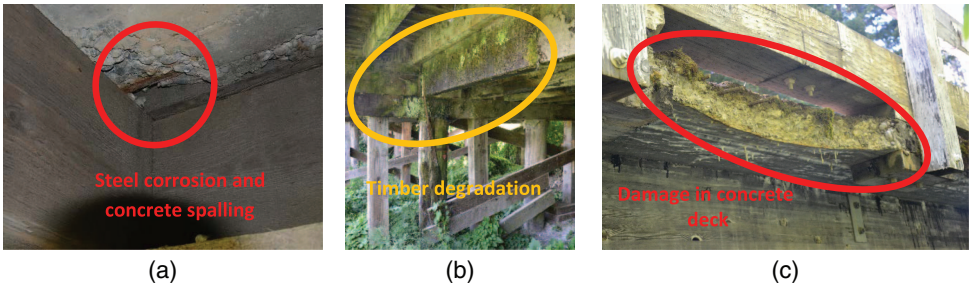

Fig. 10. (Color) Examples of (a) steel; (b) timber; and (c) concrete degradation found by the inspections. (Images by Alfredo M. P. G. Dias.)

Fig. 11. (Color) (a) Good; and (b) bad examples of concrete overhanging. (Images by Alfredo M. P. G. Dias.)

Fig. 12. (Color) Expansion joints and crack in the concrete member allowing water into the glulam girders. (Images by Alfredo M. P. G. Dias.)

Forest) up to structures located in the city of Portland, Oregon, with an average of 16,600 vehicles crossing each day.

Finally, inspection reports for five historic bridges located in Maryland whose decks were made of timber–concrete were accessed via the internet (MHT n.d.).

Knowledge from the Inspections

It is clear from the data discussed that the timber–concrete bridges do show good performance over the short and long term, and in multiple-use conditions. Most of these bridges have been renovated

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Fig. 13. (Color) Fire damage in the timber members of a TCC bridge (treated plywood was added to reduce the fire damage potential). (Image by Alfredo M. P. G. Dias.)

through the years, but have kept the original timber supporting members intact such as the viaducts near Portland, Oregon (referenced in the NBI as "SW Newbury ST Viaduct" and "SW Vermont ST Viaduct").

In spite of the general good condition of the bridges, there were several deficiencies common in a large number of bridges. The most common deficiencies found were cracks in the concrete or asphalt deck, timber degradation, steel corrosion, and mechanical damage in timber and/or concrete (Fig. 10).

Most of deficiencies were related in different ways to contact with moisture. For the timber bridges the contact of the supports, piles, and/or stringers with soil or water was the main reason, but contact with vegetation or the existence of animal nests were also found. In TCC bridge decks the presence of an upper concrete deck layer prevented most of the moisture contact with timber, which is one of the most important advantages of this system. Nevertheless, in many bridges this was not entirely effective due to poor design or performance of the bridge solutions. More specifically, two main problems were found: lack of or poorly designed concrete deck overhang (Fig. 11) and expansion joints or cracking of the concrete deck (Fig. 12). In spite of these deficiencies, the TCC bridges remain in service and, in many cases, are still providing an adequate level of service. This is likely due to the use of oil-type (creosote or pentachlorophenol) preservatives applied by pressure treatment methods for these TCC bridges.

Different overhang configurations were identified in the bridges inspected, with overhang widths that varied between 5 and 61 cm usually connected to the top of the timber member. The presence of an overhang, even with a poor design, always provided a significant level of shelter protection to the timber members on the underside. Conversely, in decks without overhangs the side timber members were always in poor condition due to the direct weathering and in some cases had been previously replaced.

The interlayer connection adopted in the various inspected bridges was quite variable, including notches, steel fasteners, and notches combined with steel fasteners. In all these situations there were no observations of malfunction of the connection system independently of conservation state of the other members. This clearly indicates that the adopted connection systems that are still used have been properly designed and protected, assuring a long-term high level of performance.

It was also clear from the inspection that a very weak zone of the TCC decks are the expansion joints and the supports. The expansion joints must be carefully designed in order to allow an adequate performance and water flow, preventing the rainwater from moving into the deck underside and saturating the supporting timber members. Cracks were commonly found in the concrete deck surface above the end supports due to girder rotational uplift. In many continuous bridges (which are the majority), the location of the intermediate supports could be identified from the deck surface due to the presence of relatively broad cracks. From underneath, there were always signs of water leakage and in many situations degradation associated with these concrete deck flaws.

Some of these bridges were in close proximity to urban areas, and in a few cases evidence of human habitation was found beneath the bridge. In these situations, remains of campfires were visible near the abutments, which damaged the glulam bridge members (Fig. 13). Fire-retardant-treated plywood was added to the glulam girders near the bridge supports to shield them from further fire damage.

Interventions have also been undertaken to mitigate damage in specific timber members, such as foundation poles or side beams. In these conditions the replacement of the timber members by steel members was often adopted (Fig. 14).

In many TCC bridges the increasing traffic demands motivated bridge widening efforts (Figs. 14 and 3). This demonstrates the TCC's long-term bridge durability: after 60, 70, or 80 years of service the condition was still good enough to not replace, but instead

(a) (b)

Fig. 14. (Color) (a) Widening; and (b) reinforcement of TCC bridges. (Images by Alfredo M. P. G. Dias.)

J. Bridge Eng., 2020, 25(3): 04020006

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to just widen. The added benefit of this approach is that the inadequate drainage issues along the bridge deck edges (curb or scupper zones) are solved.

Conclusions

From the results and discussion given in this paper, it can be concluded that TCC bridges are an effective and durable design alternative for highway bridges. Indeed, the performance of bridges in service for nearly 100 years indicates that TCC bridges can be in service for long periods subjected to very high traffic loads along with little maintenance and yet still maintain a high level performance in many cases in the rainy Northwest climate near coastal regions in the states of Oregon and Washington. The analysis of the available data for the deck, the main TCC component in these bridges, shows that in approximately 37% of the situations it is still in good condition or better, while in only approximately 4% of the situations is it in bad condition or worse. This is clearly an advantage of the composite superstructure concept of these bridges that allows for a significant reduction of the deterioration potential through the protection of the moisture contact with the timber members.

On the other hand, this research also showed that such success is closely related to a good project conception and design. Poor details in the supports or in the deck sides (concrete overhanging), which are easily avoidable at the conception and construction phase, can lead to disproportionate damage and degradation that will require significant remedial maintenance or lead to bridge decommissioning (or replacement). Indeed, the adoption of an overhang of just 5 cm, even being low and clearly insufficient, still provides a significant level of protection.

It is anticipated that the use of modern concrete, timber, and composite-type connection technologies associated with a careful detailing in the drainage systems is likely to further improve the potential of new TCC bridges in the US in the future.

Data Availability Statement

Some or all data, models, or code generated or used during the study are available from the corresponding author upon request.

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