The Use of Orthotropic Decks in Redecking of Bridges

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BRIDGE REDECKING—NEEDS AND REQUIREMENTS

A bridge deck directly loaded by heavy truck wheels and exposed to weather effects is the most vulnerable component of a bridge structure and must satisfy the most severe strength and durability demands. Failed bridge decks typically account for about two-thirds of all bridge deficiency cases. Bridge deck replacement becomes necessary where yearly deck maintenance cost exceeds the yearly life cycle cost of a new bridge deck.

In addition to providing a reliable bridge roadway, redecking is usually coupled with general rehabilitation and upgrading of the bridge aimed at enhancing its capacity and elimination or alleviation of its structural and geometric deficiencies. Therefore bridge-redecking systems should satisfy the following requirements:

- **Strength and rigidity**, to resist heavy truck wheels;
- **Good riding surface**, resistant to temperature and deicing salts;
- **Light weight**, in order to enhance the live load capacity of the existing bridge superstructure;
- **Deck acting as participating component** of the bridge structural system. The new deck should not only act compositely with the deck framing members directly supporting the roadway (stringers or floorbeams), but should also participate in sharing the live load stresses in the main carrying members of the bridge: the main girders or trusses, the stiffening members of the cable-supported bridges, etc. The 1998 *AASHTO LRFD Bridge Design Specifications*, Second Edition (AASHTO, 1998), Art. 9.4.1, expressly require that composite action of bridge decks with supporting framing, including the longitudinal and the transverse main bridge members, be developed by appropriate shear connectors in order to enhance the strength and stiffness of the structure and to prevent fatigue damage due to relative displacements of the deck structure with respect to the secondary and the primary bridge members;
- **Elimination or reduction of the number of the deck joints.** Deck joints are vulnerable to corrosion, are difficult and costly to maintain and, if not watertight, are detrimental to the integrity of the structural framing below the deck;
- **Adaptability** to specific structural requirements of the bridge being redecked;
- **Expedient installation** of the new deck with least possible traffic restrictions during construction;
- **Durability.** Service life of the replacement deck should not be less than the expected remaining useful life of the bridge;
- **Long term economy** with low yearly maintenance cost.

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CHARACTERISTIC PROPERTIES OF ORTHOTROPIC DECKS

Steel orthotropic decks, if well designed and properly detailed, are well capable of satisfying all of the above structural requirements and are especially well suited to redecking of long-span cable-supported bridges.

Orthotropic decks consist of steel deck plate stiffened by longitudinal ribs and may be of two basic varieties: with torsionally stiff closed ribs and with torsionally soft open ribs. A typical closed-rib deck is shown in Figure 1a. The ribs run continuously through the cutouts in the transverse floorbeams. The deck plate acts as a common top flange of the longitudinal ribs and the floorbeams. Closed ribs can be trapezoidal, rounded-bottom shapes or V-shapes (Figure 1b). Trapezoidal ribs have been most frequently used, however comparative studies show that V-shaped ribs are more efficient and provide better torsional rigidity. Generally, closed-rib decks are lighter, require fewer welds and have smaller exposed area to be painted. However, they are generally less fatigue resistant than the open-rib variety and are more difficult to splice in the field.

Open-rib decks (Figure 1c) are mostly made with flat bars, but more efficient T-sections or bulb shapes have also been used. Such decks may be up to 20 percent heavier than the closed-rib variety, but are largely free of secondary stresses and, therefore, inherently safer under fatigue conditions.

Both closed-rib and open-rib decks have been used in bridge redecking in the U.S. and in Canada.

GUIDELINES FOR DESIGN AND DETAILING

Orthotropic decks must be designed with proper attention to details. Practical experiences, research and testing accumulated over the five decades of orthotropic deck applications in bridge design resulted in theoretical design rules and empirical guides of good practice in detailing and welding which have been incorporated in the various design codes. If such rules are not followed, fatigue failures may occur.

The AASHTO LRFD design provisions for orthotropic decks (AASHTO, 1998) distinguish between the "load-induced" fatigue caused by net axial tension stress range which can be determined by analysis and "distortion-induced" fatigue caused by out-of-plane distortion of a plate element. Since the latter case is not easily amenable to analytical calculations, the specification stipulates that safety against fatigue should be assured by appropriate detailing based on semi-empirical guidelines given in the code. One example is the treatment of the fatigue-sensitive junction of the rib wall with the deck plate with a semi-empirical formula provided for geometric proportioning of the closed-rib deck in order to minimize the critical secondary out-of-plane bending moments in the rib walls (Art. 9.8.3.7.2). Further comments on good detailing practices are given in Wolchuk (1990).

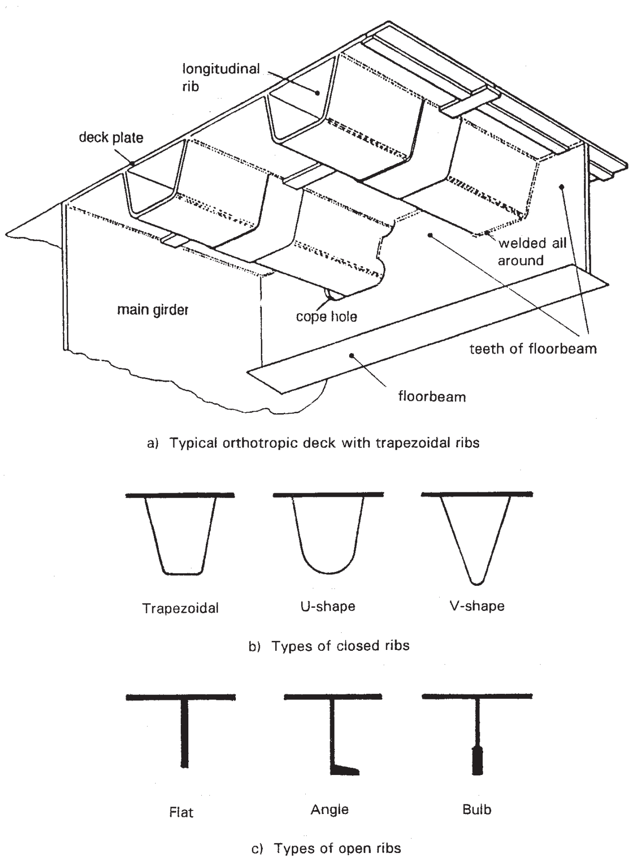


Fig. 1. Components of orthotropic decks.

Recent theoretical and experimental research of orthotropic deck behavior further clarified the fatigue problems of details subjected to complex stress patterns. The new findings are reflected in modifications of the AASHTO orthotropic deck design provisions that were adopted in May 1999 (AASHTO, 1998). It has been determined that internal diaphragms inside the closed ribs at their intersections with the floorbeams significantly alleviate the high local stresses in the floorbeam web and in the deck plate at this joint. These problems are discussed in more detail in Wolchuk (1999).

Empirical detailing rules of the specifications may suffice in the design of orthotropic decks of standard proportions. However, in cases where the deck elements are subject to unusual geometric constraints, such as very shallow webs frequently encountered in redecking, rigorous stress analysis is necessary to assure safety against fatigue. Under such restraints, floorbeam "teeth" between two closed ribs acting as shear connectors between the deck plate and the floorbeams and the connecting welds are subject to complex stresses. These are stresses resulting from the in-plane bending moments and shears, f_1, and the out-of-plane flexural stresses, f_2, due to local deformations caused by rib rotation at the support. According to Dr. J. W. Fisher of Lehigh University, fatigue strength of the rib-floorbeam intersection is governed by the combined stress components, $f = f_1 + f_2$, perpendicular to welds. This is shown in Figure 2 excerpted from the revised AASHTO Specifica-

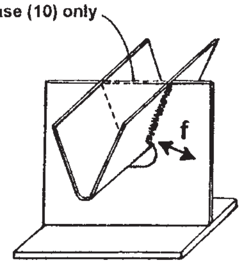
Case (10) only 	**Floorbeam web at rib / floorbeam intersection** **Fillet welds between rib and floorbeam web and between rib and internal diaphragm**	**(10) With internal diaphragm inside of closed rib, or open rib** **f = axial stress range component in floorbeam web perpendicular to weld = $f_1 + f_2$** **f_1 = axial stress range in web** **f_2 = bending stress range in web due to out-of-plane bending caused by rib rotation at support**

Fig. 2. Critical stress at rib/floorbeam intersection
(from AASHTO LRFD Specifications, Table 6.6.1.2.3-3, Revised May, 1999).

tions (AASHTO, 1998). The stress components f_1 and f_2 due to "fatigue loading" must be determined by finite element analysis and the safety of the detail evaluated in accordance with the code fatigue provisions. However, avoidance of constrained configurations and details subjected to high local stress concentrations is preferred.

Another critical issue in designing orthotropic decks is the choice of wearing surfacing, which must be considered an integral component of the deck system acting compositely with the steel deck plate. Sufficient rigidity of the deck plate and the ribs is required to assure reliable performance of the surfacing. Deck rigidity is especially important where the use of thin (⅜ in. to ½ in.) surfacing is intended, which is often employed in redecking for maximum dead weight savings.

Redecking examples in the following sections show how the various design problems were addressed in these cases and may provide lessons for future projects of this kind.

COMPLETED REDECKING PROJECTS

Table 1 gives basic information about some completed orthotropic redecking projects in the U.S. and in Canada. It is seen that in all of the cases shown, a substantial dead load reduction was achieved, ranging from 24 to 46 psf. Redecking cost (not including the needed bridge repairs), relocation of utilities, addition of inspection walkways, and other items not directly related to roadway replacement, varied from about $40 to $110 per sq. ft of roadway, depending on the specific structural problems in each case and the escalating cost of steel fabrication and erection. In most cases closed-rib decks were used, with the exception of the George Washington Bridge (T-sections) and the Benjamin Franklin Bridge (bulb-bars, Figure 4).

Some unusual features of the latter project deserve comment. Bolted deck plate splices were used because of the Owner's reservations about field welding. Furthermore, because of apprehensions about field placement of the epoxy-asphalt surfacing during wet and cold periods, the 1¼-in. thick bottom course was to be placed in the steel fabrication shop. This necessitated the use of one-sided splices of the deck plate by means of interference body bolts that had to be inserted prior to paving the deck panels. In retrospect, pre-paving of the deck panels proved to be of no advantage and caused many problems during deck installation. Watertight joints between the deck panels were difficult to achieve, which necessitated the additional expense of a waterproofing membrane that had to be installed prior to placement of the top course of the surfacing.

Specific details of these projects have been reported in literature (see references listed in Wolchuk 1992). However, two important aspects of redecking, the deck integration with the existing superstructure and the erection procedures under traffic, are worth discussing in this review.

Deck Integration

As shown in Table 1, in the initial American redecking designs no attempt was made to utilize the orthotropic deck as a participating member of the stiffening trusses or the main girders. In these cases all existing expansion joints in the roadway were retained and no shear connectors between the deck and the main members were provided. The relative displacements between the deck and the supporting stringers, and the rib connections to secondary cross beams subject to rotation, caused fatigue problems on the Throgs Neck Viaducts.

On the Golden Gate Bridge the 50-ft long roadway portions between the open deck joints are supported on pedestals mounted on existing floorbeams and act, essentially, as unanchored free-floating segments. This precluded proper seismic retrofitting of the deck. Another disadvan-

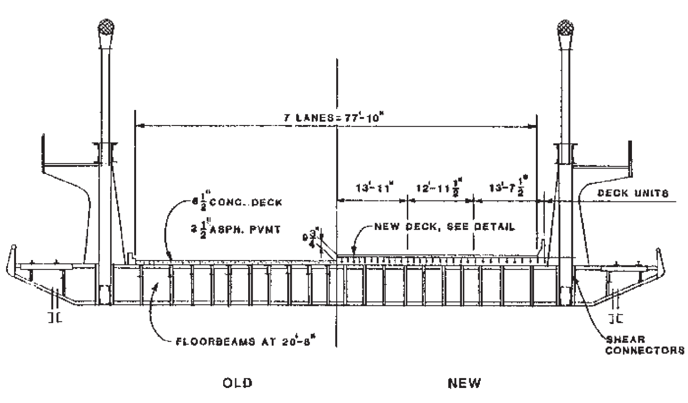


Fig. 3. Redecking of the Benjamin Franklin Bridge, Philadelphia, (Weidlinger Associates).

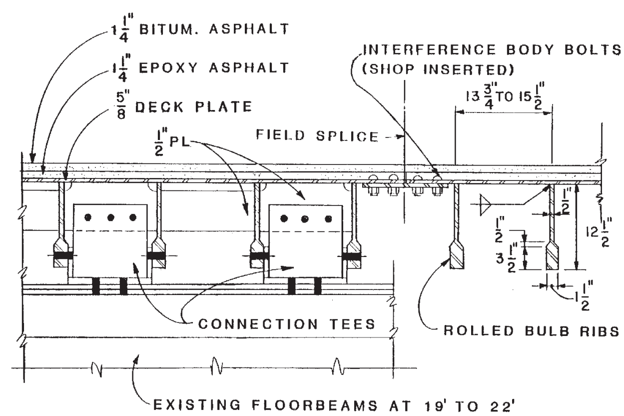


Fig. 4. Benjamin Franklin Bridge - new deck details.

Table 1. Selected Completed Orthotropic Redecking Projects in the U.S. and in Canada						
Bridge	**Lions Gate** Vancouver [a]	**G. Washington** N.Y.C.	**Golden Gate** S. Francisco	**Throgs Neck V.** N.Y.C.	**Ben Franklin** Philadelphia	**Champlain** Montreal
Year	1975	1978	1985	1986	1987	1993
Old deck weight (psf)	100	106	104	107	123	110
New deck weight (psf)	61	60	79	83	89	82
Redecking cost ($/sf) [b]	47	40	70	72	79	110
Deck integration with main members	Yes	No	No	No	Yes	Yes
Redecking work	Night	Night	Night	Night	Day	Night

[a] The 1975 orthotropic roadway is currently being replaced by a new widened orthotropic deck.
[b] Excluding bridge repairs, inspection walkways, utilities relocation and other items not related to roadway redecking

Table 2. Current Orthotropic Redecking Projects				
Bridge	Williamsburg N.Y.C.	Amesbury Mass.	Triborough N.Y.C.	Bronx-Whitestone N.Y.C
Status	Under constr.	Final design	Prelim. design	Prelim. design
Type of rib	Closed	Closed	Closed	Closed
Characteristic features	a) Limited depth available above existing floor beams. b) Minimizing dead weight is essential.			

tage is crumbling of the unreinforced edges of the 2-in. thick surfacing at the joints. Various remedial methods are currently contemplated.

On the Lions Gate Bridge and the Ben Franklin Bridge (suspension bridges) and on the Champlain Bridge (cantilever truss) shear connectors designed for interaction forces between the new deck and the main trusses were built in. This permitted elimination of all deck joints, except at the towers and at the hinges on the Champlain Bridge. A typical shear connector on the Ben Franklin Bridge is shown in Figure 5. Continuous orthotropic decks substantially increased the vertical, horizontal and torsional

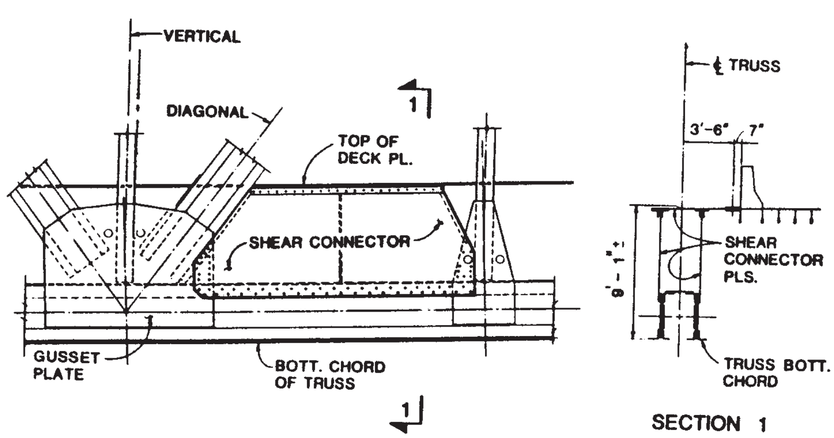


Fig. 5. Benjamin Franklin Bridge - shear connectors.

rigidities of these bridges and enhanced their structural behavior and seismic safety.

Erection Methods

In five of the six redecking cases listed in Table 1, reducing the number of roadway lanes during the day was deemed too restrictive and complete closure of one-half of the bridge at night was chosen as the preferred solution. This necessitated removal of existing concrete decks and supporting members and installation of new units during eight nighttime hours, with mandatory opening of all lanes in the early morning. This procedure was, necessarily, more costly and involved daily risk of the lanes not opening in time for the morning traffic. On the Ben Franklin Bridge (Figure 3), with seven traffic lanes and no median barrier, a more efficient daytime construction was possible. Redecking work proceeded in the longitudinal direction between fixed barriers (Figures 6 and 7). It should be noted that the roadway profile had to be raised to accommodate the needed depth of the ribs and the connections.

CURRENT REDECKING PROJECTS

Orthotropic redecking is now under construction or in the various stages of planning and design on four U.S. bridges listed in Table 2. All of these structures are suspension bridges and on all of them the very small depth available for the new deck above the existing floorbeams presents difficult structural problems, because, unlike on the Ben Franklin Bridge, the roadway profile could not be raised. Increasing traffic load and aging main cables are other concerns shared by the three long-span bridges. This makes dead weight reduction an important design requirement.

Williamsburg Bridge

Redecking of this venerable (1903) New York City bridge (Figure 8) was designed by Steinman Engineers. The orthotropic decks are replacing the heavy existing inner and outer roadways. The new decks are supported on existing floorbeams. Longitudinal shear plates are provided in alternate panels between the floorbeams and the lower truss chords. However, there are no tie plates between the deck plates of the inner and the outer roadways and the new decks are not utilized to resist the negative bending moments and to reduce deflections of the floorbeam cantilevers. Welded brackets replaced the original cantilever brackets in the 1980's. However, these were found to be vertically misaligned and had to be replaced prior to redecking by new brackets. Yet, the brackets and the deck units for the outer roadways were fabricated separately and designed to be connected by bolting, as shown in Figure 8b. In this arrangement, partial composite action of the deck panels with the brackets and the resulting shear flow in and out of the deck plate cause very unfavorable stress conditions in the shallow web "teeth" acting as shear connectors. To assess fatigue resistance of this design, very expensive full-scale fatigue tests of cantilever brackets with attached deck panels were conducted at Lehigh University resulting in adoption of the special weld details.

The design studies were completed in 1991, the deck replacement began in 1996, after completion and evaluation of the tests. By 1999, redecking of the outer and the inner

Fig. 6. Benjamin Franklin Bridge - placement of new deck panels in exterior lane.

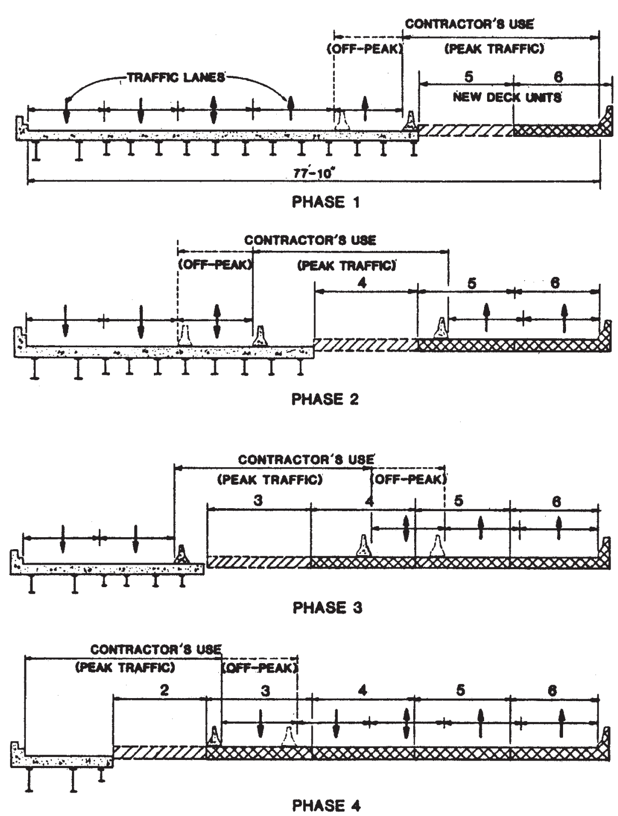


Fig. 7. Benjamin Franklin Bridge - redecking sequence.

roadway was completed on the south side of the bridge only.

Because of the fabrication difficulties, special welding details, and erection problems, the bid unit price for the new deck was much higher than that for decks with standard details on other projects.

Amesbury Chain Bridge

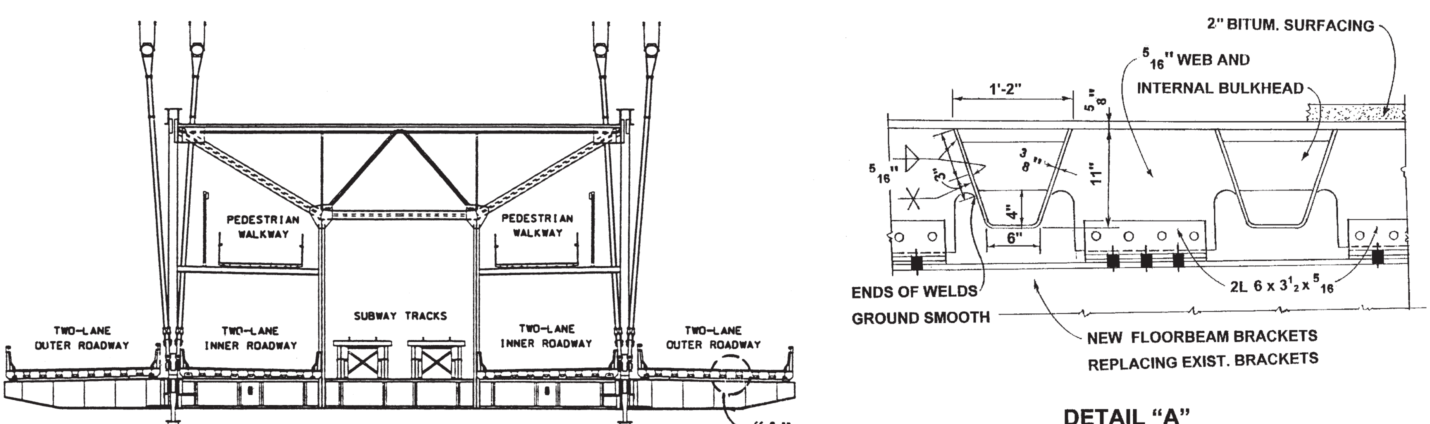
The redecking of this historic suspension bridge in Massachusetts with a single span of 243 feet (Figure 9) was designed by STV Engineers in Boston. In this case, the difficulties associated with low available depth above the floorbeams are avoided by cutting off the floorbeam top flange and connecting the transverse webs of the new deck panels directly to the webs of existing floorbeams (Figure 10). In this manner the stresses in the floorbeam "teeth" between the ribs are much alleviated and the rib rotation at the support due to unsymmetrical live loads is not unduly restrained. The V-shaped ribs were chosen for their better efficiency and to avoid sharp curvatures with resulting severe inelastic deformations and strains in the ribs fabricated by cold bending. Another advantage of this rib shape is that the secondary stresses in the rib walls confined at the intersections with the floorbeams are much alleviated (Wolchuk and Ostapenko, 1992).

Triborough Bridge

Ammann & Whitney, New York are developing the redecking design for this suspension bridge in New York City. The existing roadway consists of a concrete deck supported by secondary framing and longitudinal stringers spanning 28.8 ft between the floorbeams. The depth available above the floorbeam flanges is only 10 in. at curbs, including the allowance for surfacing on top of orthotropic deck plate. Because of this geometry, a preliminary design prepared in 1995 called for a deck with shallow trapezoidal ribs tapered over the floorbeams, which necessitated rib discontinuity and open deck joints. In this scheme, all existing rolled beam stringers had to be retained, because the deck ribs required additional secondary cross beams which had to be supported by the stringers. Based on this design a 116-ft long and 49-ft wide prototype section of the deck was constructed on the bridge in 1997 (Figure 11).

The proposed design does not permit integration of the new deck as a participating component of the stiffening trusses. This obviates the need for reassessment of the structural behavior of the suspended spans with substantially enhanced rigidity and reduced dead weight. However, the deck with open joints has serious disadvantages: exposure to corrosion of the supporting framework of the deck heavily salted in winter time, susceptibility to earthquake damage of the deck panels without positive longitudinal anchorage, and potential fatigue problems at the connec-

Fig. 9. Amesbury Chain Bridge, Massachusetts.



(a) *(b)*

Fig. 8. Williamsburg Bridge, N.Y.C. Cross section upon completion of redecking (Steinman Engineers).

tions. Likewise, this scheme precludes composite action of the new deck with the floorbeams with which it is not connected. The live loads will cause considerable relative displacements between the non-participating deck and the top flanges of the long-span floorbeams resulting in secondary deformations and stresses in the connections and associated fatigue. The AASHTO LRFD specifications specifically advise against the use of orthotropic decks not acting compositely with the supporting framing.

Several alternative solutions aiming at providing deck continuity have been suggested. One of them was similar to the scheme shown in Figure 13b, with ribs of necessary depth and rigidity running continuously over the floorbeams, whose top flanges and all existing stringers would be removed. This concept would permit deck integration of the new deck with the floorbeams and the stiffening trusses and would reduce the total bridge dead weight by about 3500 lbs. per ft of bridge length, compared with the concept shown in Figure 11. However, the structure's owners (The Triborough Bridge and Tunnel Authority) chose for the final design the scheme similar to the prototype section already in place.

Bronx-Whitestone Bridge

This suspension bridge in New York City (Figure 12) is 74-ft wide between the main cables. Originally designed for four lanes of traffic, the roadway has been subsequently widened to six lanes. Increased live load and the deteriorated condition of the main cables makes the maximum possible reduction of bridge dead weight the most important requirement of the redecking being engineered by Weidlinger Associates, New York. To lighten the weight, the existing stiffening trusses on top of the longitudinal edge girders will be removed, despite the history of instability problems of this bridge. Aerodynamic safety will be assured by installation of light-weight fairing and also by the substantially increased flexural and torsional rigidity of the

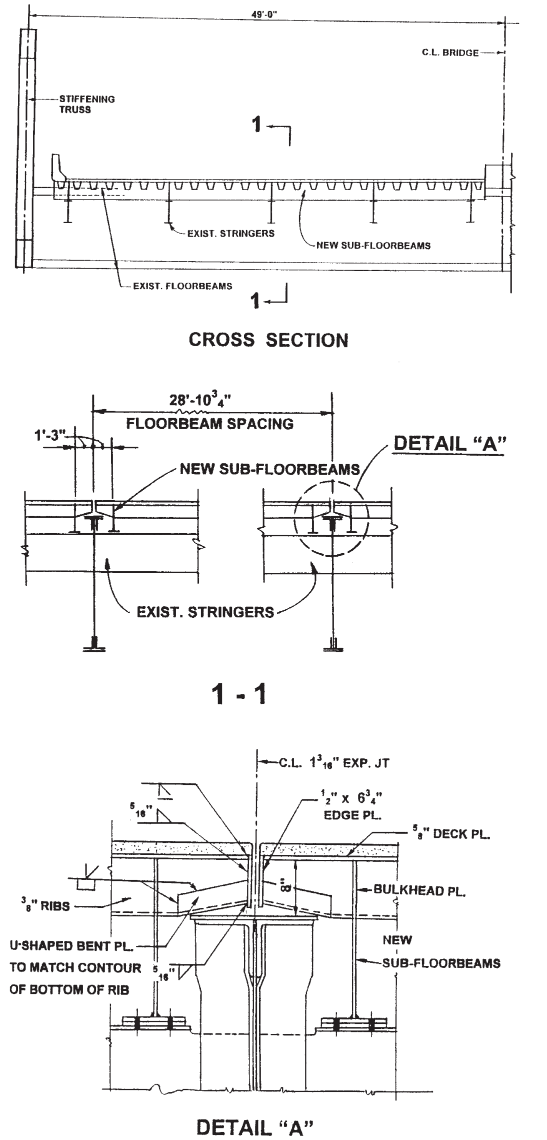


Fig. 11. Triborough Bridge, N.Y.C. Pilot installation of orthotropic redecking (Ammann & Whitney).

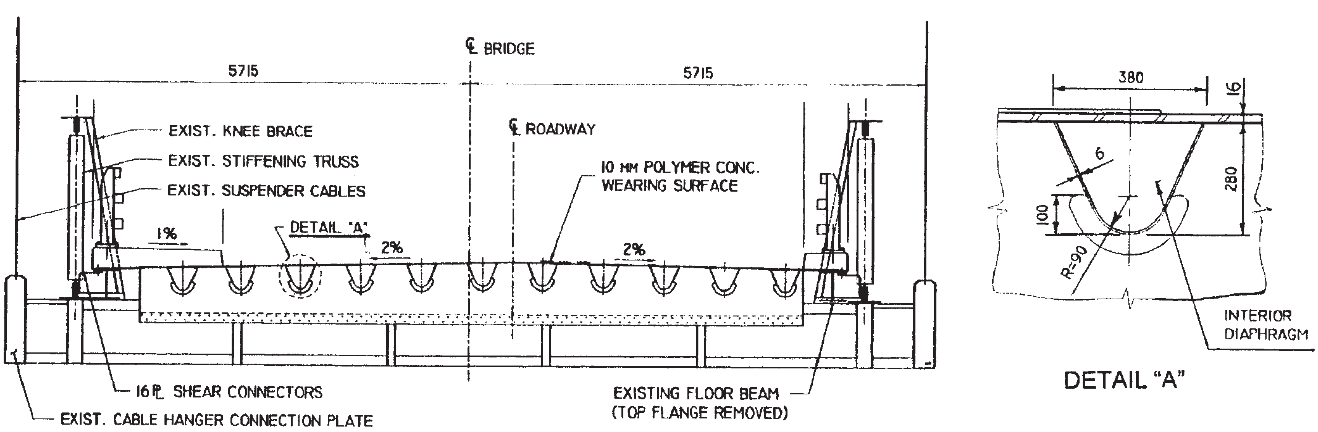


Fig. 10. Amesbury Chain Bridge, cross section after redecking (STV, Inc.).

superstructure obtained through the use of a fully integrated orthotropic deck acting as a diaphragm and as a component of a torque tube in the new configuration of the cross section.

Geometric restrictions for the new deck on this structure are similar to these on the Williamsburg Bridge. Two possible solutions are being contemplated (Figure 13). In Alternative "a" the new deck panels are mounted on top of the existing floorbeams by means of strap plates bolted to the floorbeam top flange, in which case the special precautions and weld details used on the Williamsburg Bridge might be required.

In Alternative "b" the top floorbeam flange and the flange angles would be cut off and the web stub of the new deck bolted to the existing web, (similar to the Amesbury Bridge, Figure 10). A temporary top flange will assure the necessary floorbeam capacity and stability during construction. This alternative avoids the high local stresses at the rib-floorbeam intersections and permits the use of deeper ribs, which will provide a stiffer deck, essential for good performance of the thin surfacing intended to be used. Another advantage is net dead weight savings.

Redecking may proceed transversely, across the bridge width, or longitudinally, one lane at a time. In the first case the temporary floorbeam flanges needed for Alternative "b"could be removed and re-used after each construction step. For the longitudinal procedure the temporary flanges would have to remain in place along the entire bridge length until completion of the redecking. Both, night time work, with all lanes open during the day and day time work with partial lane closures are being contemplated.

SUMMARY AND CONCLUSIONS

Orthotropic decks are well suited for replacement of deteriorating concrete decks, especially on long-span bridges where radical reduction of dead weight is necessary to meet the increasing live load capacity requirements. To be fully effective in enhancing the strength, rigidity, aerodynamic stability and seismic resistance of cable-supported bridges, the new decks must be fully integrated with the longitudinal stiffening members and the transverse deck framing members of the structure. Where the deck interaction with the bridge superstructure is disregarded in the design, various maintenance and fatigue problems invariably arise

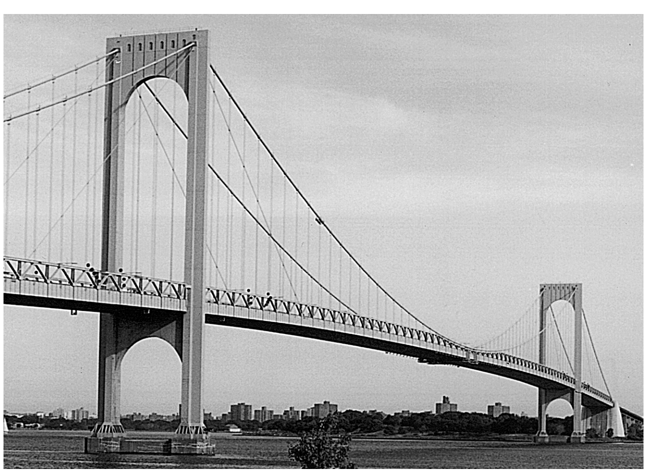


Fig. 12. Bronx-Whitestone Bridge, New York City.

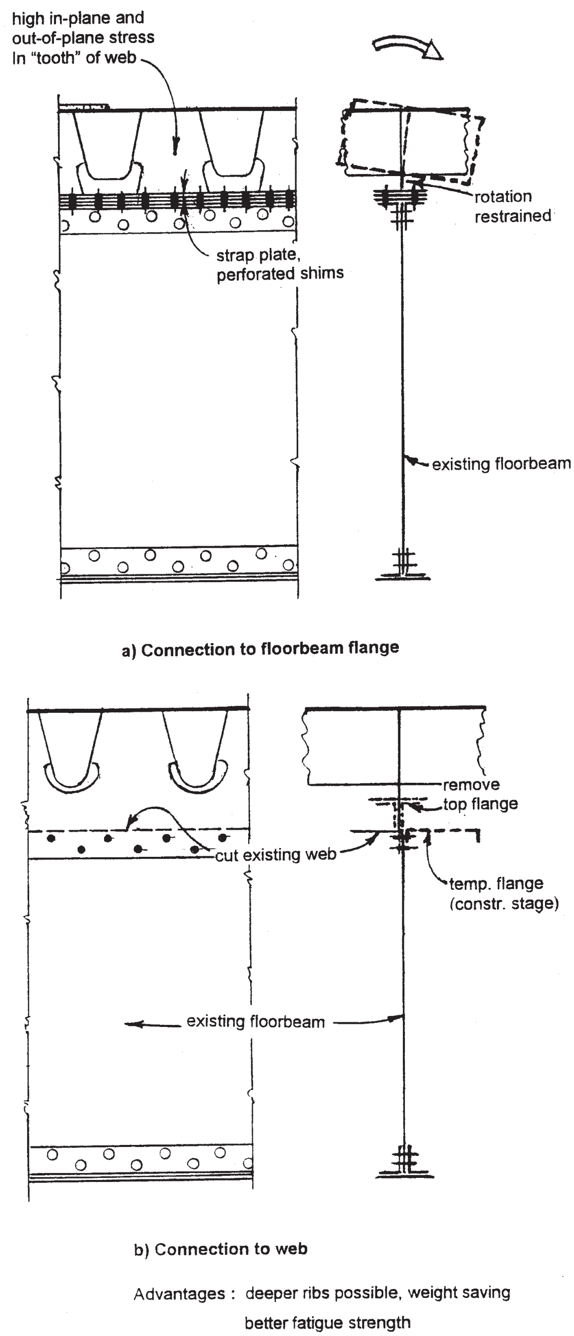


Fig. 13. Bronx-Whitestone Bridge - redecking alternatives (Weidlinger Associates).

which are very costly in the long run and may severely reduce the useful life of the bridge.

The special problems encountered in orthotropic redecking are: the design of fatigue-proof connections to the existing superstructure framing within the constraints of limited depth available for the new deck, constructibility under traffic, minimizing traffic restrictions during construction. Redecking examples given in this review illustrate how these problems were solved on these bridges, with various degrees of engineering success and cost effectiveness.

Past experiences may provide useful lessons for future projects of this kind. The following conclusions and suggestions are offered:

- Redecking design should be aimed at long term economy and increasing the useful life of the bridge. Incomplete solutions cause problems and are more costly in the long run;
- Engineering judgment should be exercised in all cases, however, recommendations on the design specifications for orthotropic decks based on accumulated experiences and research results should be respected, especially the provisions stipulating deck continuity and its integration with the main longitudinal and transverse bridge members.
- The complex problems of orthotropic redecking require much greater design effort and engineering ingenuity than routine bridge design. Compensation of the Engineer of Record on such projects should be commensurate with the task.
- Alternatives avoiding unfavorable geometric configurations are much preferable to costly solutions with details necessitating experimental verification.
- Redecking designs should be subject to comprehensive independent peer review and checking.
- Laboratory testing of aspects of orthotropic deck behavior (e. g. fatigue resistance of various surfaces or weld details) provides valuable data for the design. However, tests on large full-scale prototypes are extremely costly and time consuming and should not be considered a substitute for careful and comprehensive engineering analysis and design;
- In the same sense, large scale experimental pilot installations, with their cost ultimately borne by the bridge users and the tax paying public, are difficult to justify;
- The Engineer of Record rather than the bridge owner or operator should be the final authority on all phases of design and construction
- The ultimate responsibility to the public for redecking projects—selection of design firms with proven engineering competence, overseeing their performance which should be in accordance with principles of sound long-term economy, administration of construction expenditures—rests with the public or user-financed bridge owners who are legally obligated to maintain and preserve the bridges under their care with the least expenditure of the taxpayer's money.

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