Performance of Full-Depth Shear Keys in Adjacent Prestressed Box Beam Bridges

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Bridge decks supported by adjacent precast, prestressed concrete beams have become increasingly popular in recent years due to their ease of construction, shallow superstructure, and aesthetic appeal. In New York State prior to 1992, such structures were built by placing a number of precast beams alongside one another and connecting them through 12 in. (0.305 m) deep grouted keyways called shear keys to transfer shear forces across the structure. After the grout hardens, the beams are transversely post-tensioned and a composite, cast-in-place deck is poured over them. Prompted by the frequent appearance of longitudinal deck cracking over these partial-depth shear keys soon after construction, full-depth shear keys with more transverse tendons were adopted in 1992. A follow-up study evaluated the performance of this new full-depth shear key/transverse tie system. Results indicate that this method has reduced the frequency of shear key related deck cracking.

The use of precast, prestressed concrete box beams, bulb-tees, and voided slabs in short to medium span bridges has increased in recent years. The reasons for their popularity include ease of construction, fast installation, shallow superstructures yielding higher clearances when replacing old bridges, in-plant quality control producing more durable beams with low water-cement ratio concrete, considerable drying shrinkage due to in-plant steam curing before erection, and aesthetic appeal.

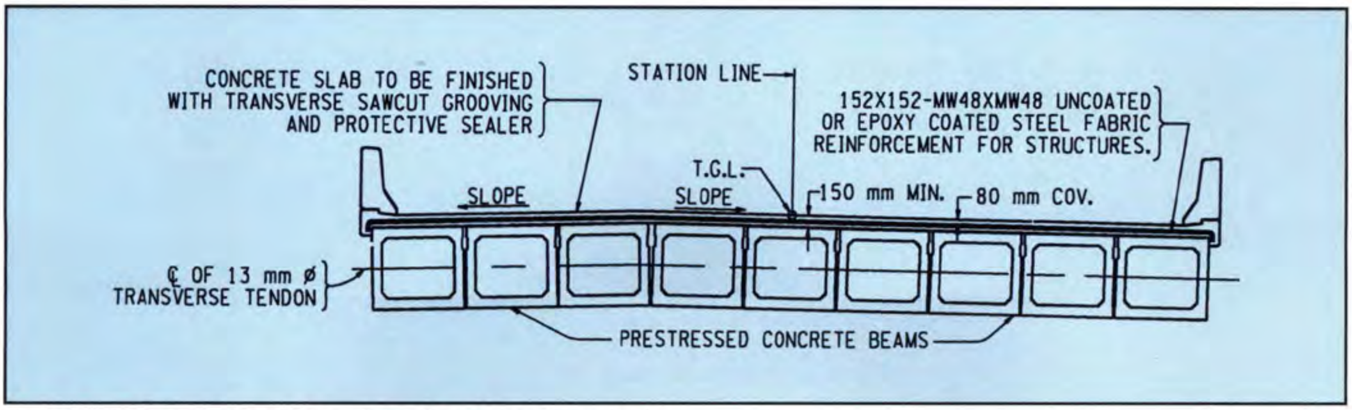

Fig. 1. Typical transverse section of an adjacent box beam bridge.

New York State has used significant numbers of these bridges with precast beam superstructures in the short to medium span range. These bridges have been built by placing a number of 3 or 4 ft (0.914 or 1.219 m) wide prestressed beams adjoining one another. They are then connected through a grouted keyway called a shear key to accommodate load transfer among adjacent beams (see Figs. 1 and 2).

Before 1992, shear keys extended about 12 in. (0.305 m) deep [9 in. (0.228 m) for hollow-core slabs] from the tops of the precast beams (see Fig. 3). Transverse tendons with 30 kips (133.4 kN) of force were used to induce transverse compression in the component system across the bridge width to assist in controlling the alignment. Spans up to 50 ft (15.24 m) long had no transverse tendons, but those between 50 and 75 ft (15.24 and 22.86 m) in length had one transverse tendon at the center. For those longer than 75 ft (22.86 m), tendons were used only at the outer quarter-points.

A cast-in-place deck, at least 6 in. (0.152 m) thick and reinforced with welded wire fabric (including a monolithic wearing surface), was placed over these precast box beams. The structure was made composite with stirrups projecting from the beams into the deck overlay.

Field personnel reported that longitudinal cracks were appearing in these concrete overlays shortly after construction (see Fig. 4). Over time, cracks developed over nearly all the shear keys and full bridge length longitudinal cracking was not uncommon. Transverse cracks were found propagating outward from these longitudinal cracks on older or heavily travelled bridges, and premature spalling was observed on some structures. Water leakage through the shear key joints was also noted.

In response to these reports, the severity of the problem was investigated in 1990 to identify potential solutions.[1] That study indicated that 54 percent of such bridges built between 1985 and 1990 had developed longitudinal cracks over the shear keys. Based on a survey of other states, several detail changes were adopted in 1992.[2]

Since then, numerous bridges with precast box beams have been built statewide. A follow-up study was con-

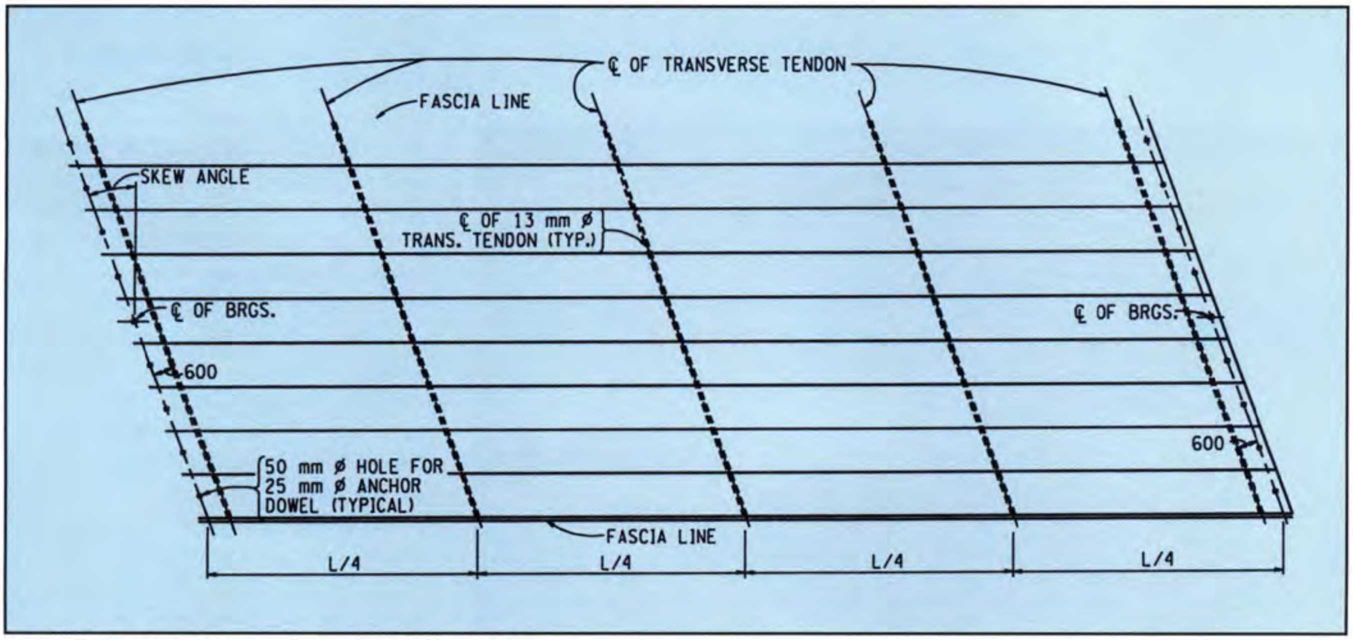

Fig. 2. Typical plan of an adjacent box beam bridge.

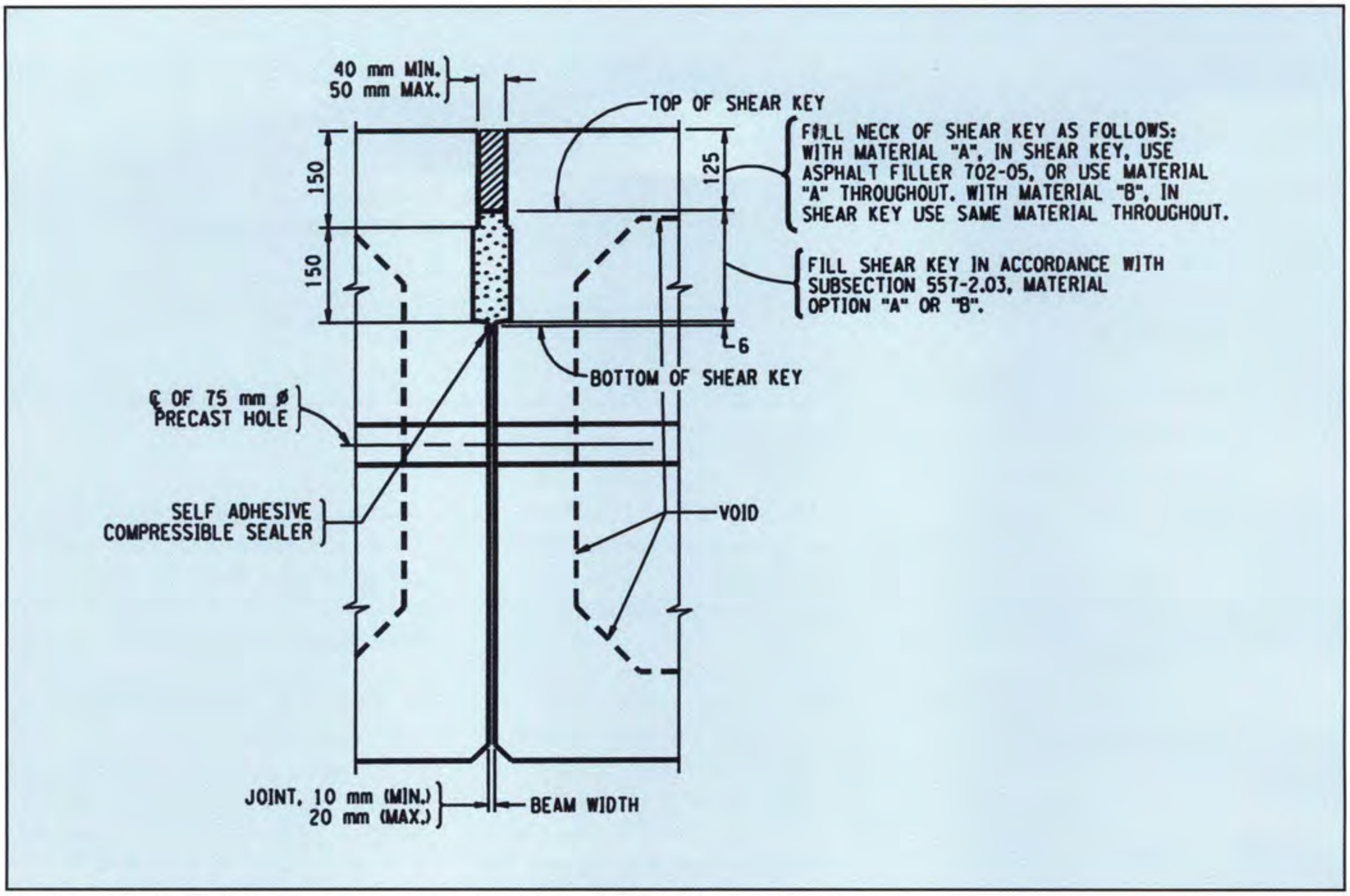

Fig. 3. Partial-depth shear key system used before 1992 (see Ref. 12).

ducted in 1996 to determine the effectiveness of the new full-depth shear key/transverse tendon system. This paper summarizes these studies and their results.

1990 STUDY

With the help of bridge inspectors, all adjacent precast box beam bridges built in New York State between 1985 and 1990 were surveyed in 1990.[1] Shear key related cracks had been reported occurring soon after construction, and the survey was limited to bridges built since 1985. This also limited the number of bridges to a manageable total of 219. A list of these bridges with precast, prestressed box beam superstructures was produced using the state's bridge inventory.

Fig. 4. Typical longitudinal deck cracking over shear keys.

Lists of selected bridges along with a survey questionnaire were then distributed to bridge inspectors, who were asked to examine the bridges for longitudinal cracks over shear keys and to mark the cracks on superstructure plans. Of the 219 selected bridges, 187 were inspected. Because the survey was conducted in the winter, it was impractical to inspect 32 of the bridges.

The returned questionnaires were then compiled and analyzed for conclusions pertaining to the extent of the problem. Table 1 indicates that more than half the bridges built between 1985 to 1990 had developed longitudinal cracks over the shear keys.

Other states were also surveyed to collect information on their shear key construction practices. Based on the information collected, particularly from Michigan, several improvements were proposed for shear key construction. In 1992, two of the suggested changes were adopted in New York's design standards:[2] (1) shear keys were increased to almost the full depth of the precast box beams (see Fig. 5);

and (2) the number of transverse tendons was increased to three for span lengths less than 50 ft (15.24 m) and to five for longer spans. It was anticipated that the new full-depth shear key with transverse ties would reduce longitudinal deck cracking by making the entire transverse section behave more as a single unit.

Table 1. 1990 survey results by year built.

Year built	Bridges inspected	Bridges showing longitudinal cracking	Percent cracked
1985	36	22	61
1986	34	18	53
1987	36	21	58
1988	33	15	45
1989	34	19	56
1990	14	6	43
Total	187	101	54

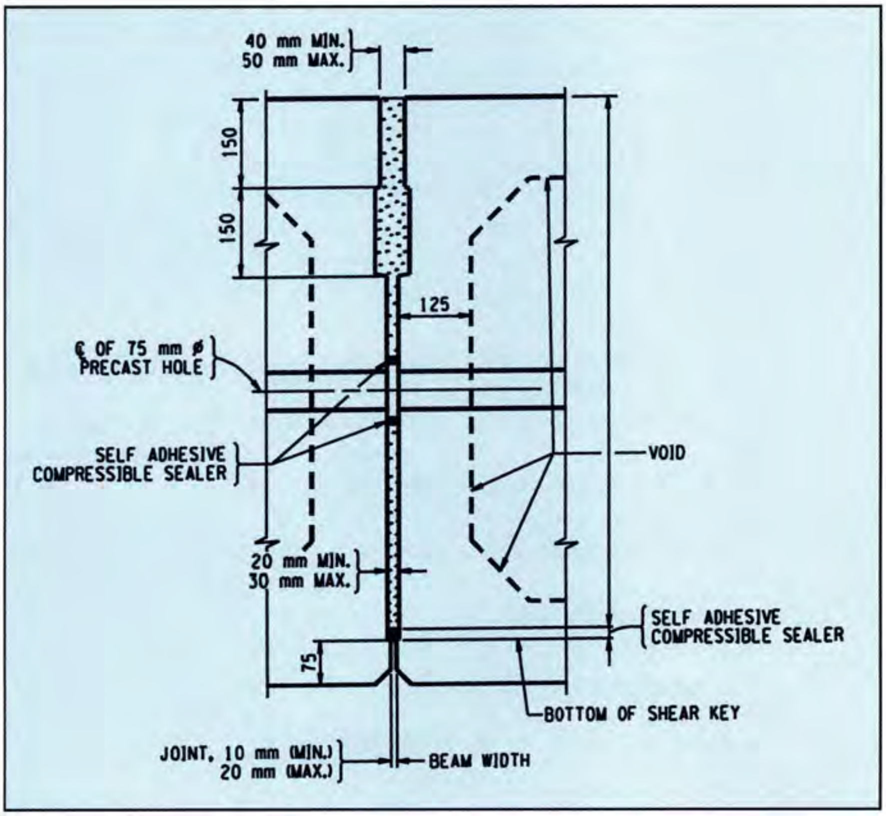

Fig. 5. Full-depth shear key system used after 1992.

1996 FOLLOW-UP STUDY

Suggested changes based on the 1990 study became effective with the state letting date of May 28, 1992. Since adoption of the changes, more than 100 such bridges have been built statewide. A follow-up study was organized to determine the effectiveness of the new full-depth shear key/transverse tendon system. This study was initiated in the first half of 1996 with another statewide inspection survey to determine the impact of the adopted design changes.

A statewide inspection was completed of all 91 adjacent precast box beam bridges built from 1992 through early 1996 using the new shear key system. A roster of these bridges was compiled using the database of bridges and a questionnaire was sent to bridge inspectors along with a list of their bridges from that database. The inspectors were asked to complete the forms after inspecting each bridge.

The survey's focus was on visual inspection of adjacent prestressed box beam bridges for longitudinal deck cracking apparently related to the shear keys. Information was requested on the number, length, and plan location of all cracks. Inspectors were also asked to report any evidence of leakage or superstructure distress.

In addition, researchers examined 10 bridges in several regions of New York and visited two bridge construction sites to observe operations in an attempt to identify possible construction related causes of shear key cracking. They discussed practices elsewhere with bridge designers in other state transportation agencies and also reviewed the literature.

Survey responses were analyzed to determine the frequency and severity of longitudinal deck cracking, as summarized in Table 2 and Fig. 6. These results show that shear key related longitudinal cracking was found on 21 bridges, or 23 percent of the sample.[3]

DISCUSSION OF FINDINGS

Inspection results (see Fig. 6 and Tables 1 and 2) were used in estimating the impact of full-depth shear keys with more transverse tendons on the frequency of longitudinal deck cracking and in determining the effect of such factors as span length, skew, average annual daily traffic (AADT), and bearing type on the incidence of cracking (see Tables 3 to 6). This study[3] resulted in the following observations:

1. Tables 1 and 2 and Fig. 6 show the impact of full-depth shear keys with more transverse tendons on the frequency of longitudinal deck cracking. Shear key related longitudinal cracking was found on 21 bridges built between 1993 and 1995, or 23 percent of those inspected. The 1990 study found shear key related cracking on 54 percent of inspected bridges built between 1985 and 1990 using the old partial-depth shear key system. In terms of quantity of inspected shear keys, a total of 874 were examined on these 91 bridges. Only 47, or about 5 percent, were associated with deck cracking. Thus, shear key cracking has been reduced significantly

Table 2. 1996 survey results by year built.

Year built	Bridges inspected	Bridges showing longitudinal cracking	Percent cracked
1993	33	10	30
1994	37	6	16
1995	21	5	24
Total	91	21	23

with the introduction of full-depth shear keys.

2. Fifteen of the 21 bridges exhibiting shear key cracking had only one or two longitudinal cracks, with widths of about $^{1}/_{32}$ to $^{1}/_{16}$ in. (0.8 to 1.6 mm). Longitudinal crack lengths varied from 5 ft (1.524 m) to the entire length of the bridge. Only five of these 21 bridges showed signs of leakage, mostly minor. At this time, no distress is visible.

3. Only two of the 21 bridges exhibited cracking at a majority of shear keys. According to the inspection personnel, both carry high truck volumes, which may have caused the observed severe cracking.

4. The frequency of shear key cracking appears unrelated to maximum span length or total bridge length (see Table 3).

5. Bridge skew angle apparently is not directly related to the frequency of shear key cracking. As shown in Table 4, the frequency of cracking is about the same in bridges with no skew as in those with a high degree of skew (30 degrees or more).

6. Bridges with higher average annual daily traffic (AADT) appear to be more susceptible to shear key related cracking (see Table 5). Those with AADTs of 5000 or more exhibited more cracking than those with AADT values less than 5000.

7. Bridges with fixed bearings had more cracks than those with expansion bearings, but the difference was not very significant (see Table 6).

PROPOSED IMPROVEMENTS

Results of the 1996 statewide survey showed a significant reduction in the frequency of shear key related longitudinal deck cracking since adoption of the new shear key/transverse tie system. However, efforts for further improvement of this system should continue. Based on the literature search, site visits, and consultations with bridge designers in other transportation agencies, the following possible improvements have been proposed.

Shear Key Installation

Proper grouting during construction is essential for better performance of shear keys, and stringent quality control is needed during grouting operations. Construction personnel should be aware of the importance of adhering to recommended specifications. It is important that keyways be free of debris. Before grouting, keyway surfaces should be sandblasted, cleaned, and pre-wetted. The proper water-cement ratio in the grout should be maintained. No grout should be placed during a rainfall. Grout should not leak from shear key bottoms or through transverse tendon ducts.

Without stringent on-site quality control, shear keys will continue to be the weakest points in adjacent precast beam bridges. Thus, awareness of their function for good performance must be stressed. Alternative materials for keyway grouting applications should be considered after a thorough evaluation of existing studies in the literature concerning their performance under field loading conditions.[4-7]

Increased Reinforcement in Concrete Overlays

El-Remaily et al. have discussed the transverse structural behavior of

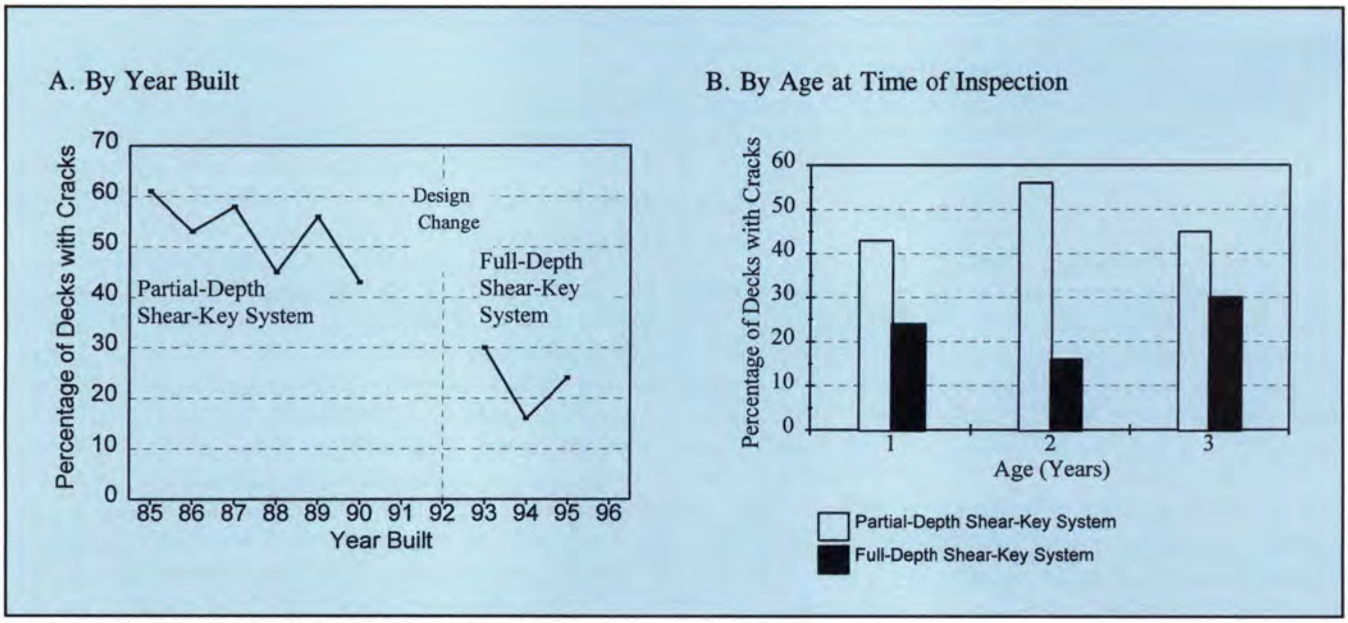

Fig. 6. Frequency of longitudinal deck cracking.

adjacent prestressed concrete box beam bridges.[8] If box beams are not fully connected, transverse moments may develop that induce tensile stresses, causing longitudinal cracking and longitudinal hinging along the shear keys. However, if box girders are transversely restrained at the top and bottom, longitudinal hinging is less likely so the load is distributed across the entire bridge width and the deflected shape becomes a smooth curve.

According to Stanton and Mattock,[9] in multi-beam bridges with cast-in-place decks, vertical loads are distributed transversely by flexure, torsion, and shear in the slab and to some extent by the diaphragms. Martin and Osborn[10] also reported that both shear and bending must be transferred at transverse joints between girders to control both translational and rotational deformations. Because joints between members often cannot transmit moments transversely, they act as hinges transferring the vertical load across the joint by shear.

Some states use a heavy, structurally composite deck for effective transverse transfer of vertical loads. Table 7 compares deck overlays now used in four other states. Current New York standards require a 6 in. (152 mm) minimum thickness concrete slab with W7.5x7.5 welded wire fabric reinforcement spaced at 6 in. (152 mm) in each direction. This corresponds to a reinforcement ratio of 0.2 percent transversely and is equal to the minimum reinforcement required to control shrinkage and temperature stresses.

Table 7 shows that other states use 0.5 percent or more transverse reinforcement. Thus, it is recommended that concrete overlay reinforcement be increased by providing either welded wire fabric with a larger cross-sectional area or No. 5 reinforcing bars at 12 in. (305 mm) spacing in both directions. It is anticipated that greater transverse stiffness of the deck overlay will help transfer bending and shear stresses among adjacent box beams, further reducing the probability of shear key cracking.

Table 3. 1996 inspection results — effect of span length.

Span length (ft)	Bridges inspected	Bridges showing longitudinal cracking	Percent cracked
< 50	23	6	26
50 to 75	39	9	23
> 75	29	6	21

Table 4. 1996 inspection results — effect of skew.

Skew (degrees)	Bridges inspected	Bridges showing longitudinal cracking	Percent cracked
0	35	11	31
1 to 30	39	5	13
> 30	17	5	29

Table 5. 1996 inspection deck results — effect of traffic volume.

Average annual daily traffic	Bridges inspected	Bridges showing longitudinal cracking	Percent cracked
0 to 2000	35	5	14
2001 to 5000	21	5	24
5001 to 10,000	19	6	32
10,001 to 25,000	16	5	31

Table 6. 1996 inspection results — effect of bearings.

Bearing type	Bridges inspected	Bridges showing longitudinal cracking	Percent cracked
Expansion	38	7	18
Fixed	39	11	28

Table 7. Transverse deck reinforcement used by various states.

State	Minimum deck thickness (in.)	Deck reinforcement	Transverse steel (sq in. per 1 ft width)	Transverse reinforcement ratio (percent)
Kentucky	5	#5 bars at 12 in. in both directions	0.31	0.52
Michigan	6	#3 bars at 10.5 in. longitudinally and #4 bars at 6 in. transversely	0.40	0.55
New Jersey	5	#5 bars at 12 in. in both directions	0.31	0.52
New York	6	6x6 W7.5x7.5 wire fabric	0.15	0.20
Pennsylvania	5	#4 bars at 12 in. longitudinally and #5 bars at 8 in. transversely	0.46	0.70

Note: 1 in. = 25.4 mm; 1 sq in. = 645.2 mm^2; 1 ft = 0.3048 m.

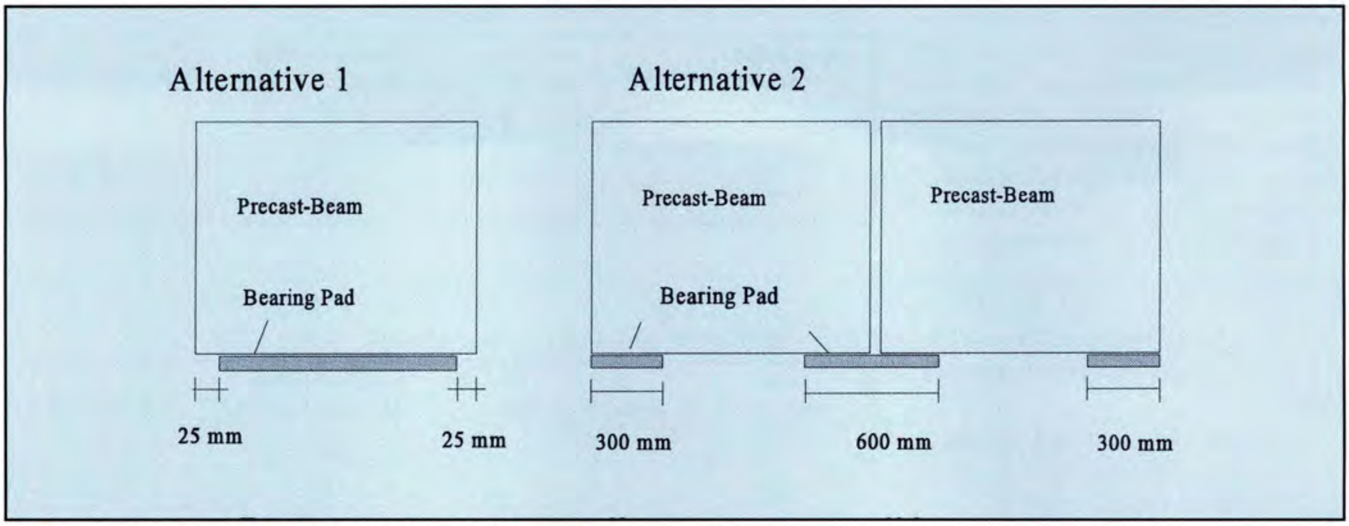

Fig. 7. Alternative arrangements for bearing pads.

Full-Width Bearing Pads

According to current New York State standards, bearing pads or blocks must be as wide as half the beam width, although this may allow beams to rock, rotate, or twist along their longitudinal axes.[11] Several other state transportation agencies use either two pads per beam or pads almost as wide as the full beam width. Based on these details, alternative bearing details are recommended (see Fig. 7).

Greater Post-Tensioning Force

The AASHTO load and resistance factor design (LRFD) specifications recommend a minimum average effective post-tensioning pressure of 250 psi (1.72 MPa), but contact area over which this prestressing force is assumed to act is not specified.[8] For instance, this area could be either diaphragm-to-diaphragm, the full-girder side face, or just the top shear key area.

The spacing between the diaphragms or their size are also not specified. Most states (including New York) now use a 30 kip (133.4 kN) force at one or more locations to tie all the precast box beams together. Michigan, however, uses much higher post-tensioning forces of 82.5 or 104.5 kips (367 or 465 kN), depending on the beam depth.

El-Remaily et al.[8] proposed a design procedure based on grid analysis to compute the bending moment in diaphragms, and recommended a post-tensioning force of 202 kips (898 kN) at midspan of an 80 ft (24.4 m) long, 52 ft (15.8 m) wide box beam bridge subjected to HS-25 loading. Thus, the 30 kip (133.4 kN) force used for transverse post-tensioning may be insufficient.

If future studies reveal continuing problems with shear key performance, Michigan's experience and El-Remaily's proposed design method should be considered. Also, only one post-tensioning strand is now used at each diaphragm location. Providing two strands (one each near the beam top and bottom) would provide more uniform compression on the contact area between adjacent beams (i.e., increased transverse flexural capacity). This alternative arrangement for post-tensioning is shown in Fig. 8.

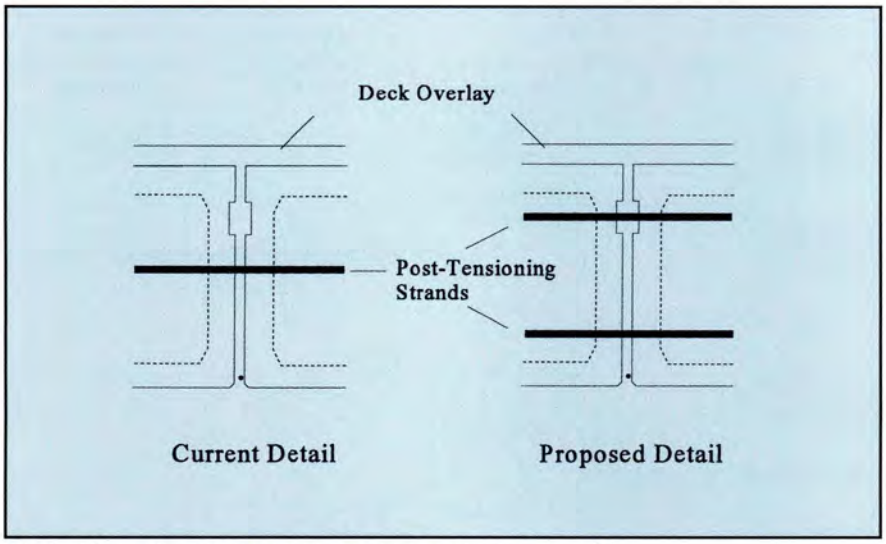

Fig. 8. Alternative arrangements for post-tensioning strands.

CONCLUDING REMARKS

Full-depth shear key performance of precast beam bridges has been surveyed in New York State, resulting in evidence of shear key related cracking in only 23 percent of inspected bridges. A total of 874 shear keys were inspected on these 91 bridges and of these, only 47, or about 5 percent, of shear keys were associated with deck cracking. A 1990 survey had reported such cracking on 54 percent of inspected bridges, indicating significant improvement with the new full-depth shear key/transverse tendon system.

RECOMMENDATIONS

Based on the experience of New York and other states, the following steps, singly or in combination, are recommended for further improvement in shear key performance:

1. Use alternative arrangements for bearing pads beneath the adjacent beams (such as full-width bearing pads).

2. Use a higher reinforcement ratio in the concrete deck overlay, either by increasing the size of the welded wire fabric or by providing No. 4 or No. 5 reinforcing bars in both directions at a spacing required by the design.

3. Provide higher transverse post-tensioning forces and two tendons over the depth of the beam at each post-tensioning location.

ACKNOWLEDGMENTS

The views expressed in this paper are those of the authors and do not necessarily represent the views of the New York State Department of Transportation. This work was partially funded by the Federal Highway Administration, United States Department of Transportation. The cooperation of numerous engineers in inspecting bridges within a short time period is gratefully acknowledged. Duane Carpenter and David Rettig provided valuable help in drafting the survey questionnaire and establishing the list of target bridges. Osman Hag-Elsafi, Robert J. Perry, Mathew Royce, Arthur Yannotti, and Joseph Savoie provided useful comments.

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