Deck Joints: the Weak Link in Bridge Structures and Life-Cycles

Bojidar Yanev
Executive Director,
Bridge Inspection & Management
Department of Transportation,
Adjunct Professor, Columbia University,
New York City
55 Water St, New York, NY 10041, USA
212 839 4181
byanev@dot.nyc.gov
Corresponding author
ABSTRACT

The condition of a bridge network over three decades is reviewed. The bridges comprising the network are considered as networks of structural elements. Deck joints are identified as the weak link in both networks. Typical modes of failure are shown for the joints most commonly used in New York City and the Metropolitan area. Bridge management options are examined in the context of deck joint performance.

Key words: bridge, deterioration, joint, life-cycle, management.
1. INTRODUCTION

Processes and products commonly fail at discontinuities. Engineering structures most frequently fail at joints. This is particularly true of bridges where joints function under dynamic conditions in aggressive environments. Hence, the statement that “the only good joint is no joint” is claimed by numerous contributing authors. That thinking is pursued in two directions. On bridges of up to several relatively shorter spans numerous publications, including (1) and (2) recommend jointless bridges and integral abutments. The large cyclic displacements of long-span bridges are accommodated by special expansion devices, such as the modular joints, designed and manufactured to detailed specifications including installation, maintenance and replacement. Between these two extremes, both options co-exist in the vast population of multi-span bridges serving vehicular traffic for many decades. The joints of such bridges can be limited to fewer locations and designed for larger movement, or located at every second span and built for smaller displacements and greater impact.

The performance of all alternatives has been reported extensively, in Syntheses, such as (3) and (4), as well as in the National Bridge Inventory (NBI) Biennial Inspection reports. The cumulative findings identify deck joints as the weak link in the bridge structure, as well as in the management process. Consequently, their deficiencies must be addressed on all stages and levels of the bridge life-cycles. On a network level, the American Society of Civil Engineers (AASHTO) Load and Resistance Factor Design (LRFD) Bridge Specifications recommend amplifying the design live load for joints by an impact factor of 75%. On project levels, joint malfunctions persist in construction, maintenance and operation. The problems of the product must therefore be examined on all stages and levels of the process.

2. THE NEW YORK CITY BRIDGE NETWORK

In 2013 New York City is responsible for 789 vehicular and pedestrian bridges with approximately 5,000 spans and a total deck area of 1.5 million m². Among them are the Brooklyn Bridge (1883), Williamsburg (1903), Manhattan (1909) and Queensborough – Ed Koch (1909), over East River, 25 moveable bridges (swing, lift, bascule and retractile) and many multi-span viaducts. The average age of the bridge population is approximately 80 years. According to New York State standards, the bridges are inspected at least biennially and all elements in all spans are rated from 7 (new) to 1 (failed). The overall bridge condition rating R is calculated according to the formula of Eq. (1).

\[
R = \sum_{i=1}^{13} w_i \ R_i
\]

where:
- \(R_i\) - lowest condition rating of element i (Table 1, row 1) observed on the bridge during a regular inspection (not necessarily in the same span)
- \(w_i\) - weight assigned to element i (Table 1, row 2).
The elements \( i \) and their respective weights \( w_i \) are shown in Table 1.

### TABLE 1. Elements and weights in the NYS DOT bridge condition formula

<table>
<thead>
<tr>
<th>( w_i )</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Element</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
<td>13</td>
</tr>
<tr>
<td>2</td>
<td>Bearing anchor bolts, pads</td>
<td>6</td>
<td>5</td>
<td>8</td>
<td>5</td>
<td>6</td>
<td>10</td>
<td>5</td>
<td>1</td>
<td>2</td>
<td>8</td>
<td>4</td>
<td>8</td>
<td>4</td>
</tr>
</tbody>
</table>

Yanev and Chen (5) and Yanev (6) used the condition ratings generated by the mostly visual biennial inspections and Eq. (1) to obtain a range of bridge and element deterioration patterns. Yanev (7) explores the equilibrium between the annualized costs of capital reconstruction & component habilitation for a large bridge network and the linearized element and bridge deterioration rates. Figures 1 show the bridge condition ratings for 1990, 1998 and 2011, plotted with respect to the bridges’ age (from “year built” according to the inventory).

After more than 30 years of accrual, the condition rating database may seem suitable for statistical evaluations as well. Subjecting the cloud of data points to a regression analysis however, obscures significant differences between them. The age, function, quality of inspection and invested work for the bridge population is highly non-homogenous. Numerous full and component rehabilitations are continually conducted without modifying the “year built” entry in the inventory. The four East River crossings have absorbed nearly $US 4 billion over the last 30 years. Since changing the “year built” entry to the last major rehabilitation would be no less deceptive, the inventory retains the original 1883, 1903, 1909, and 1909, respectively. Condition ratings \( R > 4.5 \) cannot be reliable for bridges older than 50 years.

The average life-span of the entire bridge population consistently surpasses the 75 years recommended by AASHTO. The annual expenditures for capital reconstruction & component rehabilitation over the same period however, have reached $US 600 million. Given the known unit construction costs, such expenditures correspond to the much briefer life-cycles represented by the worst cases shown in Figs. 1-a, -b, and -c. Thus the meaningful “deterioration rates” governing the equilibrium between annual capital expenditures and conditions are not the average but the steepest ones. By the end of the examined period they no longer fall below 3 (not functioning as designed). The equilibrium between serviceable bridge conditions and related expenditures is a desirable “steady state” for a large bridge network. Nevertheless, it has been achieved at an average annual direct cost of roughly $US 400/m² of bridge deck area.
a) 1990

1998 Condition Rating vs Age (No Ped)

b) 1998
c) 2011

Figure 1: Condition ratings versus age for the New York City bridges.

As reconstruction/rehabilitation eliminate the worst bridges from the global network, reducing direct and user life-cycle costs becomes a priority. To that end, maintenance/preservation can similarly eliminate the fastest deteriorating bridge elements from the structural network.

3. THE BRIDGE ELEMENT NETWORK

The New York State database contains ratings of all bridge elements in all spans and is well-suited for modeling structures as networks of elements. Figures 2 show the condition ratings for critical bridge elements included in Eq. (1) with respect to their age. Based on condition ratings in all regions of New York State, Agrawal and Kawaguchi (8) modeled element deterioration rates by Markov chains and Weibull distributions, ultimately opting for the latter. The obtained life-cycles are consistently around 75 years, in agreement with the average patterns shown in Figs. 2. As in bridges, so in their elements however, statistical models clash with experience and expenditures. Most importantly, the improvement of the worst bridge conditions, shown in Fig. 1 – c for 2011, is not matched by a corresponding improvement in the worst conditions of the elements in Figs. 2 for the same year. The early deterioration of certain critical bridge elements is liable to affect decks, primary members and the overall bridge condition. The task is therefore to improve the steepest deterioration rates of critical bridge elements before their condition affects the structures and ultimately, the network.
a) primary members

b) concrete decks
c) wingwalls

2011 Age Vs Wingwall Rating

2011 Age Vs Bearings Rating

d) bearings
Figure 2: Deterioration vs. age for critical bridge elements.

e) backwalls

f) joints
Partial optimization of maintenance expenditures is achieved in (9) and (10) by correlating deterministically bridge maintenance levels and annualized life-cycle costs for the bridges of New York City. The method assigns importance factors to 15 maintenance tasks, recommended by (11), to the condition ratings of the 13 structural elements of Eq. (1). The shortest lives of the bridge elements are obtained from inspection records, such as those in Figs. 2. The elements are treated as independent.

The next step is to consider the bridge elements as structurally related networks within the bridge network. In order to quantify the mutual dependence between the performance of the 13 elements of Eq. (1), Yanev and Richards (12) proposed the matrix shown in Table 2. Along the rows, values ranging from 0 to 1 signify the impact of each element on the rest. Hence, the values along the columns should reflect the vulnerability of each element to the malfunctions of the others. The matrix is assembled deterministically, as were the vector of weights $w_i$ in Table 1 and the matrix of importance factors correlating maintenance tasks with element deterioration rates (7, 9, 10).

Table 2. A sample “correlation” between the conditions of critical bridge elements

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0.5</td>
<td>0.5</td>
<td>0.2</td>
<td>1</td>
<td>1</td>
<td>0.3</td>
<td>0</td>
<td>0</td>
<td>0.3</td>
<td>0.1</td>
<td>1</td>
<td>0.8</td>
<td>6.7</td>
</tr>
<tr>
<td>2</td>
<td>0.7</td>
<td>1</td>
<td>0.3</td>
<td>0.3</td>
<td>0.4</td>
<td>0.4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3.1</td>
</tr>
<tr>
<td>3</td>
<td>0.7</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.8</td>
<td>0.4</td>
<td>0</td>
<td>0.4</td>
<td>0.1</td>
<td>0.2</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2.3</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>0.3</td>
<td>0.4</td>
<td>0.1</td>
<td>1</td>
<td>1</td>
<td>0.2</td>
<td>0</td>
<td>0</td>
<td>0.3</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>6.3</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>0.5</td>
<td>0.5</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0.9</td>
<td>0</td>
<td>0.8</td>
<td>0.8</td>
<td>7.5</td>
</tr>
<tr>
<td>7</td>
<td>0.2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td>0.8</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td>2.4</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
<td>1</td>
<td>1</td>
<td>0.8</td>
<td>0.9</td>
<td>0.2</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
<td>0.8</td>
<td>0.5</td>
<td>0.2</td>
<td>0.1</td>
<td>3.9</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.8</td>
<td>0.2</td>
<td>0.2</td>
<td>0</td>
<td>0.3</td>
<td>0.9</td>
<td>0.5</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.7</td>
<td>1</td>
<td>8.6</td>
</tr>
<tr>
<td>11</td>
<td>0.7</td>
<td>0.2</td>
<td>0.4</td>
<td>0</td>
<td>0.7</td>
<td>0.8</td>
<td>0.4</td>
<td>1</td>
<td>0.4</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0.7</td>
</tr>
<tr>
<td>13</td>
<td>1</td>
<td>0.5</td>
<td>0.5</td>
<td>0</td>
<td>0.8</td>
<td>1</td>
<td>1</td>
<td>0.6</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0.7</td>
<td>1</td>
<td>9.1</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vulnerability</td>
<td>8.1</td>
<td>4.2</td>
<td>4.8</td>
<td>2.6</td>
<td>7.2</td>
<td>8.7</td>
<td>4.7</td>
<td>4.6</td>
<td>4.1</td>
<td>7.2</td>
<td>4.7</td>
<td>5.6</td>
<td>6.8</td>
<td>73.3</td>
</tr>
<tr>
<td>(14)+(14)</td>
<td>14.8</td>
<td>7.3</td>
<td>10.8</td>
<td>4.9</td>
<td>13.5</td>
<td>16.2</td>
<td>7.1</td>
<td>8.7</td>
<td>8.0</td>
<td>15.8</td>
<td>12.3</td>
<td>11.3</td>
<td>15.9</td>
<td></td>
</tr>
</tbody>
</table>

The values in Table 2 reflect knowledge of structural behavior and the worst case trends exhibited in Figs. 1 and 2. The “impact” and “vulnerability” indexes in Table 2, col. 14 and row 14, respectively, are comparable to the values of $w_i$ in Table 1, with some
significant differences. The most vulnerable elements of Table 2 are bearings, anchor bolts & pads, followed by primary members and decks. Leading in impact are joints, decks and wearing surface. Highest cumulative scorers are primary members, joints, decks.

The inspection data of Figs. 2 and the matrix of Table 2 identify deck joints as the weak link in the bridge structural chain. Their deterioration is among the fastest and their impact – the greatest. That distinction is shared by scuppers and paint, which are not included in Eq. (1). Their inclusion in the equation and in Table 2 would improve the model of the structural vulnerability to deterioration.

4. DECK JOINTS: THE WEAK LINK

In 2013, 677 of the 789 bridges on the New York City inventory were vehicular, with approximately 4,000 spans. The expansion joint were 1409 and the total number exceeded 3,000. In all of the represented joint types, observed practices, malfunctions and failures confirm the findings of (4). Figures 3 - a through - n illustrate typical malfunctions in common joints. Prevalent are the steel armored joints with rubber seals shown in Figs. 3 – a through g. Rarer are the “cushion” joints, as in Fig. 3 - i. The extreme traffic hazards of failing armor and cushion joints are temporarily mitigated by steel plates, as in Fig. 3 – k, by paving over, as in Fig. 3 – h or by plug joints (Fig. 3 – j). Butt joints with or without steel edges (Fig. 3 – k – n) are used in decks with minimal thermal movements. Elastomeric concrete headers, as in Fig. 3 – l, m, are replacing the regular concrete ones. Polymer poured in place sealants are used in decks without armor (Fig. 3 – n). Proprietary inflatable seals are used for joints accommodating slightly larger displacements than the butt joints.

From its founding in 1988, the New York City Bridge Division has recognized deck joints as the weak link in structural performance and safety, and a primary driver of both direct and user costs. NYC DOT Bridge Management developed the form shown in Fig. 4 in order to inventory and address joint malfunctions. Typical findings include the following:

Compression seals: debris accumulation, ruptured, protruding, missing.
Poured-in-place seals (butt joints): drying out, debonding;
Steel armor: loose, broken, protruding;
Cushion joint: broken bolts, loose, missing plates;
Concrete header: cracked, sagging, broken, exposed re-bars;
Elastomeric header: poor adhesion of sealant;
Concrete decks: broken corners;
Asphalt pavement: cracked, sinking;
Plug joints: cracked, eroded strip, bulging, sinking;
Modular & Finger joints: Not included herein due to their special functions and properties. Particularly sensitive to misalignment, impact and debris accumulation.
a) armor joint, asphalt

b) monodeck, torn angle

c) monodeck, protruding seal

d) monodeck, missing seal
e) armor joint, concrete header  
f) armor joint, concrete header

g) armor joint, concrete header  
h) paved over steel plate
i) cushion joint  

j) plug joint

k) paved over butt joint

l) butt joint, elastomeric header
m) elastomeric concrete header  n) monodeck, poured in place seal

Figure 3. Typical malfunctions in deck joints.

Figure 4. Deck joint inspection form, NYC DOT.
The impact of joint failures on susceptible structural elements is irreversible. Figures 5 show damage to bearings, pedestals, fascia and entire piers under expansion joints. Figure 5 – c shows an entire span under reconstruction as a consequence of joint leakage to the pier. The rest of the bridge appears in good condition.

a) bearings and pedestals

b) fascia
c) piers

Figure 5. Structural consequences of joint malfunctions

5. CONCLUSIONS

Despite their well studied malfunctions, deck joints remain the primary weak link in the designed / constructed product and process of bridge management. Each stage of the life-cycle fails to deliver the best product to the next, while all elements of the product fail to resist and transmit the applied loads.

Design: According to Table 2, joints and decks have the highest “impact” on the rest of the elements in the structural “network”. They, in turn, typically fail under the impact of live loads. For joints, AASHTO LRFD has increased the live load impact factor from 33% to 75%, raising the following questions:

- How far around the joint should the impact factor apply? There is abundant evidence that if the steel armor does not fail, it destroys the header and if the header holds, it breaks away from the deck. Decks are primarily designed and reinforced for flexure, but fail in “shear fatigue” (13).

- What are the appropriate fatigue live loads? Fatigue design is well advanced for steel, but not for the other involved materials, including concrete, elastomeric concrete, polymer sealants, and so on.
While these questions remain under consideration, most joints are not designed for specific local conditions, but adopted from “state-of-the-art” supplies. There are no warranties covering their expected load cycles.

Construction: Steel and concrete joint elements, and compression seals are usually installed according to design specifications. Minor misalignments of spans can impose unsustainable loads on joints. The poured in place seals are sensitive to ambient conditions and material preparation. As a result their performance is highly uneven. Adhesion to elastomeric and regular concrete headers is poor.

Maintenance: Compression and poured in place seals are not regularly cleaned and replaced. Loose steel angles are not bolted until they break or break the concrete header. Bearings, pedestals and troughs under expansion joints are not cleaned. Plug joints can be installed as emergency replacement of cushion joints for 2 - 4 years, depending on the traffic and the demand for structural movement.

All joint-related maintenance tasks, including the inspections implied in the form of Fig. 4, incur high direct and user costs. Extensive traffic closures are inevitable. Traffic and water under the bridge impose specific restrictions on remedial work. As a result, maintenance delegates joint repair to reconstruction. Major rehabilitation, as in Fig. 5 – c, typically concentrates at piers damaged by expansion joints.

Operation: Vehicular traffic is growing in volume and gaining in weight. Joints are regularly damaged by overweight vehicles and by the direct impact of snow-plowing and other equipment. Weigh-in-motion systems and enforcement must be considered in future design, construction, maintenance and operation not only for long-span bridges, but for multi-span structures on high volume traffic corridors as well. Joints lend themselves to instrumenting for monitoring of the live load cycles.

Preservation: The term was introduced by the Federal Highway Administration (FHWA) in 2008 (14). The deficiencies described thus far appear to exceed the capacity of regular maintenance, whereas they cannot stand alone as reconstruction projects. Bridge preservation would comprise of tasks bridging this gap and arresting deterioration in elements with high impact before it has affected the vulnerable decks, primary members and piers. The elements comprising the bridge condition formula in Eq. (1) and enumerated in Tables 1 and 2 have thus far been chosen in order to prioritize rehabilitation / reconstruction. The trends exhibited in Figs. 1 and 2 suggest that other elements, such as paint and scuppers, might be significant in allocating funding to bridge preservation.

Management: Joint failures are ultimately management failures. In a robust operation, no stage of the process or element of the product should inherit or transmit deficiencies to the others. The safe and cost-effective lifecycle of structures and networks requires redundancy, which in turn depends on continuity. In a typical bridge network, where 35% of the spans have expansion joints, the benefits of addressing these discontinuities before the need arises to address the entire structures are considerable.
Disclaimer: The material presented herein expresses the views of the author and not those of any organization.

6. REFERENCES


