TSUNAMI WAVE LOADING ON A BRIDGE DECK WITH PERFORATIONS

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ABSTRACT :

Tsunamis have damaged bridges to various extents in the 2004 Indian Ocean Tsunami. This paper reports an experimental investigation of the effect of perforations in the girders and parapets on the horizontal tsunami loads. The results reveal that the maximum pressures impinging on the front face of the pier and deck are 4.5 and 3 times the hydrostatic pressure at 80mm nominal wave heights. The percentage of force reduction of the bridge deck with 10% perforated girders and 60% perforated parapets is found to be close to the percentage of perforation area in the deck. However, it is also noted that perforations in the bridge deck can substantially reduce the tsunami forces acting on it throughout the force time history. Thus, less damage to the bridge is anticipated for the bridge deck with perforations in girders and parapets.

KEYWORDS: Tsunami, bridge deck, experiment, perforation, loading, pressure

1. INTRODUCTION

Evidences of partial to total collapse of bridges and extensively displaced bridge decks in the 2004 Indian Ocean tsunami (Unjoh, 2005; Sheth et al., 2006; and Ballantyne, 2006; Maheshwari et al., 2006; Scawthorn et al., 2006; Lukkunaprasit and Ruangrassamee, 2008) have prompted investigation of bridge performance under tsunami forces. The design of bridges to prevent these failures has not been thoroughly explored and the provision of an effective countermeasure remains an important issue. As bridges are an important lifeline structure which needs to achieve immediate occupancy performance after a disastrous event, the tsunami loading on bridges has to be investigated in view of the paucity of related established studies.

The experimental studies of tsunami forces on bridges have been conducted by Kataoka et al. (2006), Shoji and Mori (2006) and Iemura et al. (2007) recently. The latter study investigated the wave action on an I-girder bridge deck which was located on a dry bed while the others modeled the box type bridge decks which were placed on a wet bed at certain height of still-water. Shoji and Mori (2006) located the bridge deck on abutments whereas Kataoka et al. (2006) and Iemura et al. (2007) simplified the models by neglecting the bridge piers (personal communication with the authors). No pressure or force measurements were recorded by Shoji and Mori (2006). Kataoka et al. (2006) found that the slowly-varying drag force on the bridge deck which followed the impulsive force, averaged over a 0.5 s duration, can be well predicted with wave height-dependent formula stipulated by the Japan Port and Harbour Association (JPHA, 1999). On the other hand, drag force with drag coefficient of 1.1 is proposed for estimating tsunami forces on the bridge deck by Iemura et al. (2007) in which the maximum forces and maximum flow velocity were found to occur practically at the same time.

The wave propagation on shore and the wave-structure interaction are complex, which in turn has resulted in the inadequacy of the theoretical approach for tsunami force estimation for bridges using the current state of the art. Therefore, wave flume experiments were conducted with the purposes to investigate the actions of wave on a bridge system and thus to assess the effectiveness of perforation in bridge girders and parapets in reducing the tsunami-induced forces on the bridge. The present study investigated two configurations of bridge decks, one was the common bridge deck with solid girder and parapets (hereafter referred to as solid bridge deck) and the other one was the proposed bridge deck with perforated girders and parapets (hereafter defined as perforated bridge deck).

2. EXPERIMENTAL SETUP

A 1/100 single column bridge bent scale model with six I-girders and parapets was tested in a 40m long with 1m × 1m cross section wave flume (Figure 1). Two bridge configurations were investigated as shown in Figure 2, viz. the original prototype configuration typical in Thailand with solid girders and parapets, and the modified one with 10% and 60% perforation in its girders and parapets, respectively. The details of the bridge deck are given in Table 1. Tsunami waves were simulated by an abrupt release of a predetermined quantity of water from an elevated tank. The severely hit Phuket Beach in Thailand with 0.5 degree slope was adopted as the typical beach profile. The solitary-like tsunami waves broke into bores, propagated as surges on dry bed (as described by Camfield (1994)) and impinged on the bridge model which was installed at downstream of the wave flume. The force was measured by a high frequency load cell mounted at the base of the model while the pressure was obtained from pressure gauges which were installed on the front face of the base of the pier (P1) and the front (P2f) and back (P2b) faces of the mid-span of the front bridge girder. Two nominal wave heights of 65mm and 80mm were performed. The nominal wave height is defined as the maximum flow depth at the bridge site in the absence of the model.

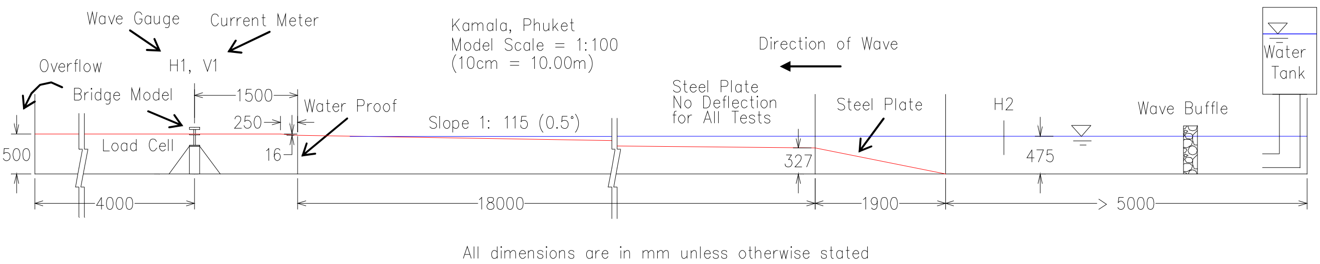

Figure 1 Test setup

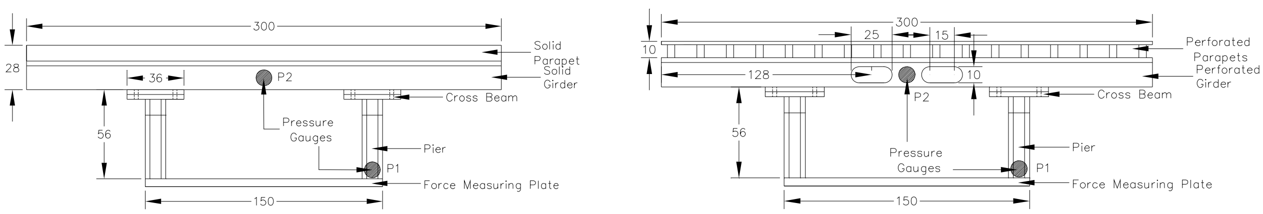

Figure 2 Solid deck (left) and perforated deck (right) models

Table 1 Details of bridge deck

Deck models	Solid	Perforated
Vertical projection area of each girder	4500mm^2	4500mm^2
Vertical projection area of each parapet	3000mm^2	3000mm^2
Vertical projection area of the slab	900mm^2	900mm^2
Perforation area (percentage) in girders	0mm^2 (0)	450mm^2 (10)
Perforation area (percentage) in parapets	0mm^2 (0)	1800mm^2 (60)

3. RESULTS AND DISCUSSION

Figure 3 shows the snapshots indicating the sequence of the generated tsunami flow striking the bridge model (highlighted in dotted lines in the figure for clear presentation) at 80mm nominal wave height. Two length scales with the length interval of 1cm were attached on the side wall of the flume. The wave propagates from the right side to the left side of the model. Prior to the installation of the bridge model, the wave height and flow velocity at the location of the model (as denoted as H1 and V1 in Figure 1) were measured and these values were correlated with the wave height at a reference point (H2 in Figure 1) located at the upstream of the wave flume. During the execution of the tests, the wave height at H2 was only recorded in order to minimize the interference of the flow regime adjacent to the model due to the installation of measuring instruments.

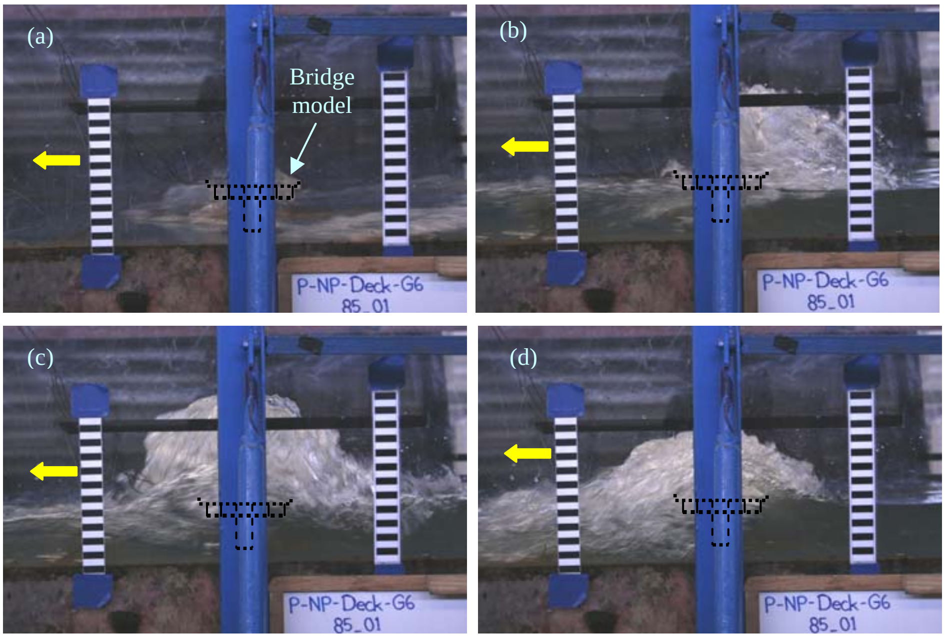

Figure 3 Sequence of the wave attacking the bridge model at 80mm nominal wave height

Figure 4 illustrates the recorded time histories of wave height (H1), flow velocity (V1), total force (on the piers and deck) and pressures for the 65mm and 80mm nominal wave heights. Table 2 summarizes the results of wave heights, forces on the bridge deck and pressures at the front and back faces of the front girder normalized with the maximum wave heights at H1. At the wave front, the surge travels with shallow wave height but with the maximum flow velocity as depicted in Figure 4a. The wave strikes the bottoms of the bridge piers initially and splashes upward to the soffit of the cross beam. The pressure at the base of the pier attains a maximum value up to almost 4.5 times the hydrostatic pressure (see Figure 4c and Table 2). At this instant, no pressure reading is recorded at the front and back faces of the front girder as shown in Figures 4d and 4e, respectively. Thus, the resulting force, depicted as the first peak of the force time history in Figure 4b, is essentially the wave force acting on the piers only.

Thereafter the wave height increases but the flow velocity decreases. When the wave reaches the girders, it splashes up (Figure 3b), collapses on the deck (Figure 3c) and then overtops the deck (Figure 3d). The upward splashes of two and three times the incoming wave heights are observed at the 65mm and 80mm nominal wave heights, respectively. This produces the highest force in the second peak of the time history. The pressure gauges at the front girder start registering the readings (Figures 4d and 4e). It is found that the front face pressure on the front girder varies in the same trend with the recorded force. The maximum pressures at the front face girder are in the range of 1.7 to 2.2 times (for 65mm nominal wave height) and 2.2 to 3 times (for 80mm nominal wave height) the hydrostatic pressure. However, the maximum pressures at the back face of the front girder are slightly less than the hydrostatic pressure for both nominal wave heights.

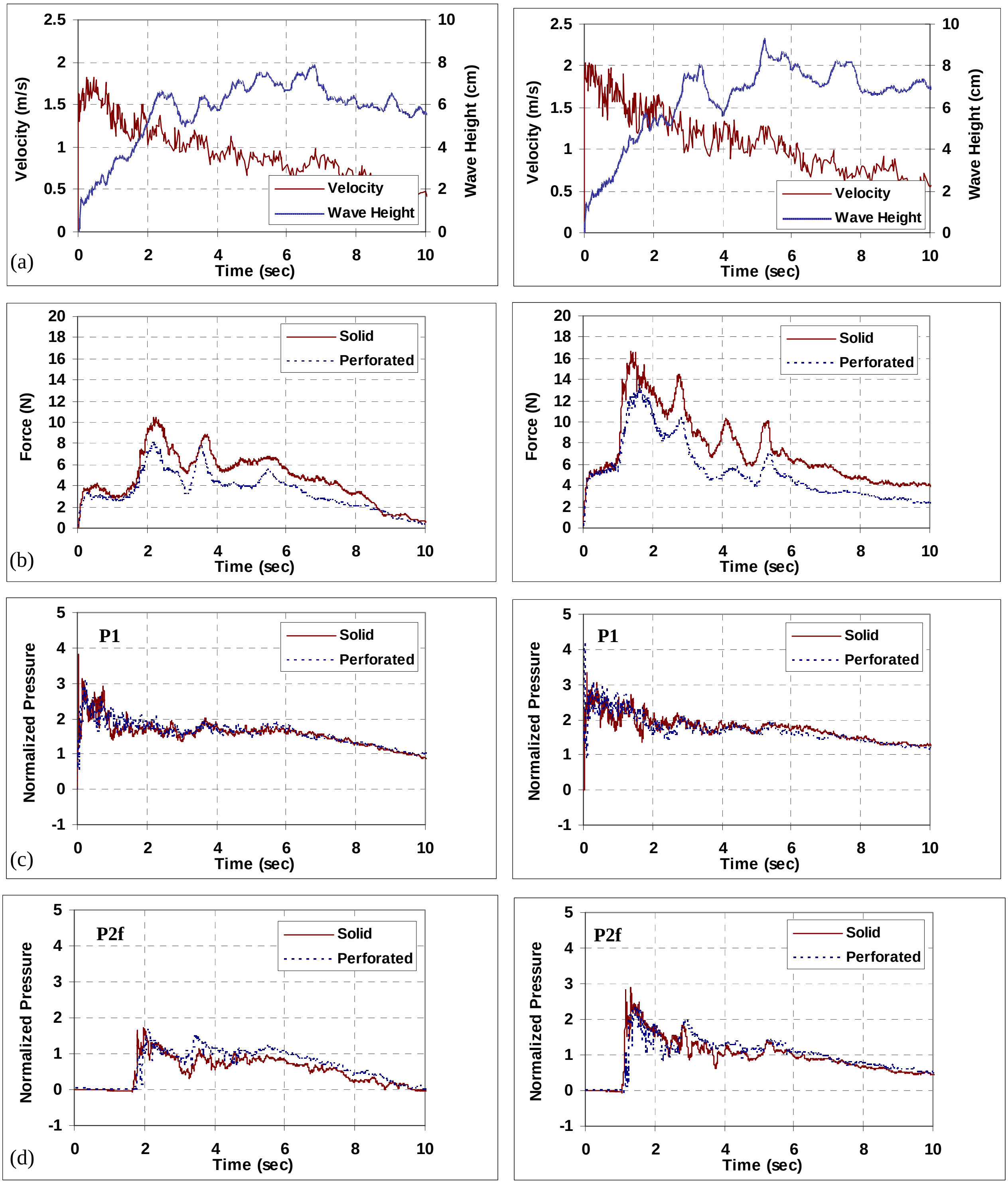

Figure 4 Correlation among (a) wave height and flow velocity, (b) total wave force and (c-e) pressures on the bridge model with solid deck and perforated deck at 65mm (left) and 80mm (right) nominal wave heights

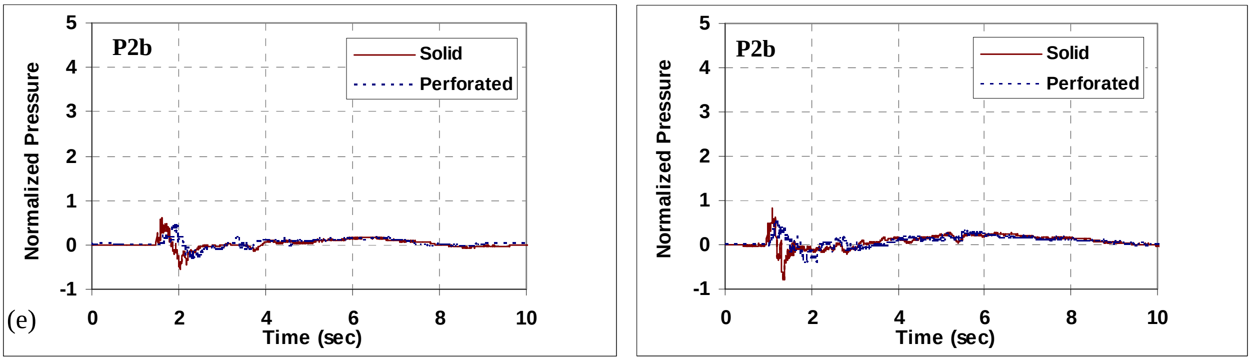

Figure 4(Cont'd) Correlation among wave height, flow velocity, total wave force and pressures on the bridge model with solid deck and perforated deck at 65mm (left) and 80mm (right) nominal wave heights

Table 2 Summary of results

Test	Deck model	Maximum wave height (cm)	Peak force on the deck (N)	Perforated / solid	Normalized peak pressure at the base of the pier	Normalized peak pressure at the mid-span of the front girder (front face)
1	Solid	6.58	9.4		4.3	1.7
2	Solid	6.62	8.8		3.4	1.9
3	Solid	6.80	8.6		3.8	1.7
			Mean= 8.9	-	3.8	1.8
4	Perforated	6.78	7.2		4.1	2.2
5	Perforated	6.71	6.3		3.5	1.7
6	Perforated	6.80	6.5		3.1	1.7
			Mean= 6.7	0.75	3.6	1.9
7	Solid	8.32	12.4		3.5	2.7
8	Solid	8.34	12.5		4.4	2.9
9	Solid	8.41	13.0		3.0	3.0
			Mean=12.6	-	3.6	2.9
10	Perforated	8.02	9.4		3.3	2.4
11	Perforated	8.23	8.8		3.2	2.2
12	Perforated	8.18	8.7		4.2	2.4
			Mean= 9.0	0.71	3.6	2.3

The second peak forces, which are the highest forces in the time histories, are picked up as the maximum forces that impinge on the deck (Table 2) after subtraction of the forces acting on the piers from the stand alone pier model. The force time histories on the bridge deck are presented in Figure 5. The wave force at 80mm nominal height increases to its peak more rapidly than the one at 65mm nominal height. Substantial reduction in forces has been witnessed in the perforated bridge deck. Unfortunately, the difference of pressure distribution in solid and perforated decks cannot be clearly distinguished due to the limited pressure measurement along the deck. However, higher fluctuation in the pressure record of the perforated deck is detected at 80mm nominal wave height (Figure 4d).

In general, bridge deck with perforations in the girders and parapets can reduce the forces at the peak and throughout the whole time history at both the considered nominal wave heights. Based on the summary in Table 2, the peak force reductions of 25% and 29% are obtained for 65mm and 80mm nominal wave heights, respectively. The peak force reductions are close to the area reduction of the entire vertical projection area of the deck, which is 27%. This seems to be simply caused by the reduction of the attacked area of the deck. However, substantial reductions are gained as far as the whole time histories are concerned. The mean forces exerting on the bridge with perforations, which are the time average of the areas below the force time history, are determined to be 33% and 39% lower than the values in solid deck bridge at 65mm and 80mm nominal wave heights, respectively.

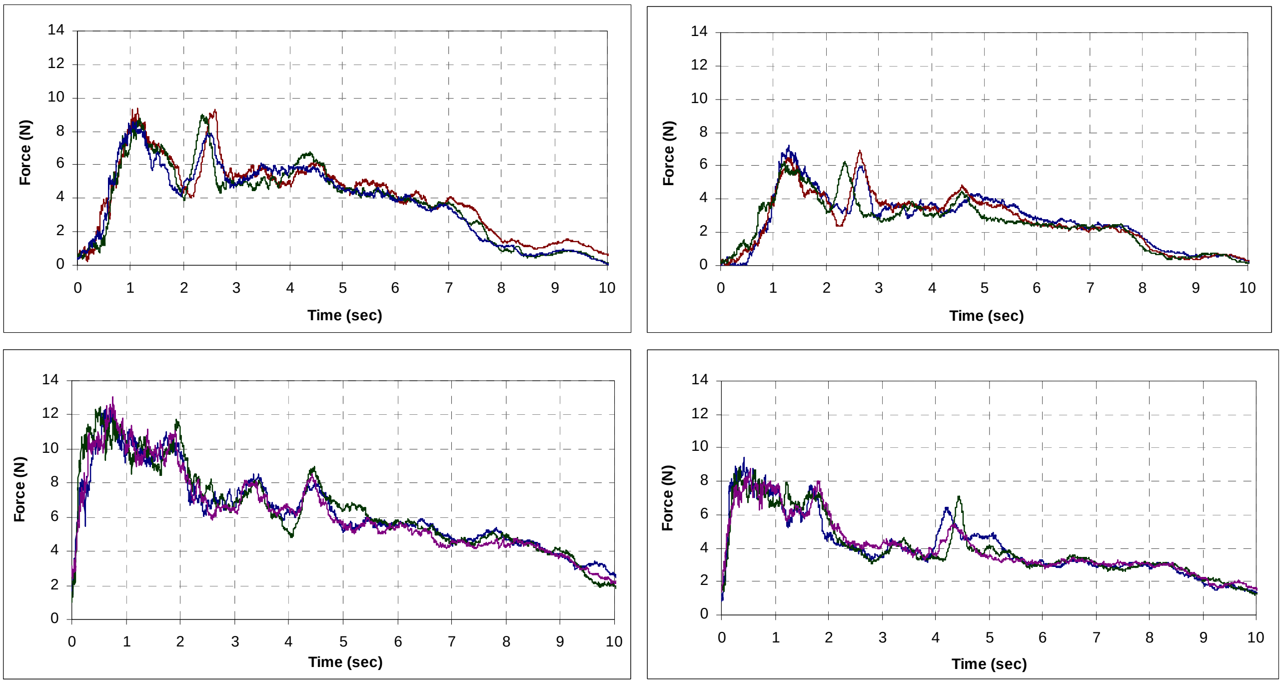

Figure 5 Force time histories on the solid (left) and perforated (right) bridge decks at 65mm (top) and 80mm (bottom) nominal wave heights

4. CONCLUSIONS

The experimental results reveal that the maximum pressures at the bottom of the bridge pier are as high as 4.5 times the hydrostatic pressure for both bridge models with solid and perforated decks at 65mm and 80mm nominal wave heights. In addition, the maximum pressures at the front face of the mid-span of the front girder are about 2.2 to 3 times the hydrostatic pressure, depending on the nominal wave height. The perforation in girders and parapets reduces the average peak forces by about the same rate of the reduction in vertical projection area of the deck. However, substantial reduction in the forces thereafter throughout the force-time history is found. Thus, less damage to the bridge is anticipated for the bridge deck with perforations in girders and parapets.

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