３D-FE Analysis of Void Scale Causing Damage to Steel-Concrete Sandwich Deck

by

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Steel concrete composite decks with concrete sandwiched between top and bottom steel plates. Placing highly flowable concrete inside therefore may produce a void between the top deck and concrete owing to the change in volume while the concrete hardens or the accumulation of air while the concrete is placed. The void may cause local damage to the pavement or top steel plate and is likely to deteriorate the durability of the deck. In order to identify the scale of void that may cause damage to steel plates, three-dimensional finite element analysis was conducted. As a result, it was found that cracking occurred at bolted connections on the top steel plate when a wheel load acted at a point at a depth of 3mm or greater where the void was larger than the spacing between bolts.

Key words: *decks sandwiching concrete with steel, fatigue cracks, voids, three-dimensional finite element analysis*

1. Introduction

An increasing number of steel concrete composite decks have recently been adopted to meet the need for reducing member weight to save manpower for field work or to enhance the seismic resistance of members. One of the composite decks is a deck with concrete sandwiched between top and bottom steel plates bolted to concrete (referred to as a sandwiched deck below). Placing highly flowable concrete inside may produce a void between the top deck and concrete owing to the change in volume while the concrete hardens or the accumulation of air while the concrete is placed. It has been confirmed that the void may cause local damage to the pavement or top steel plate and is likely to deteriorate the durability of the deck.

Then, the authors reproduced the damage based on the data obtained in field investigations to make verifications concerning the void causing the damage. No void causing the damage has yet to be quantified. Further examinations are required. In this study, therefore, voids are examined by three-dimensional finite element analysis in the horizontal and vertical directions.

2. Present of sandwiched decks

2.1 Design concept

In the design of a composite deck, the stiffness of cross section is generally calculated based on Navier's hypothesis on the assumption that top and bottom steel plates or bottom steel plate is integrated with concrete, and the stresses acting at various positions are checked. In reality, however, no bond can be expected between steel plates and concrete, so Navier's hypothesis never becomes true. As a result, great deformation occurs (Fig. 2). In the design of a composite deck, therefore, a friction model is used for finite element analysis without regarding the bond between steel plates and concrete[1]. Sandwiched decks also exhibit much different characteristics in compression from those of ordinary concrete decks[2] because internal concrete is restrained by steel plates and bolts. In the design of a sandwiched deck, a constitutive equation is applied that counts on the effect of restraining by steel (Fig.4). Using a contact-friction model and a constitutive equation counting on the effect of restraining has made design possible that is more compatible with test results. The behavior of the composite deck is shown in Fig. 2.

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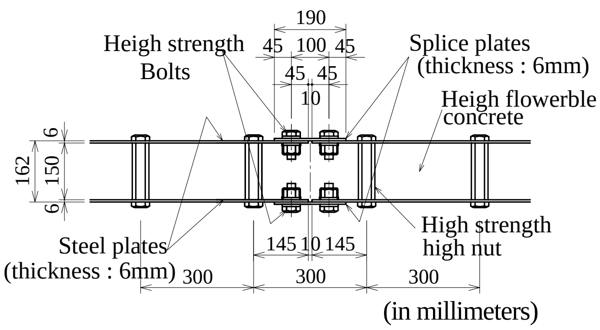


Fig. 1 Structure of sandwiched deck

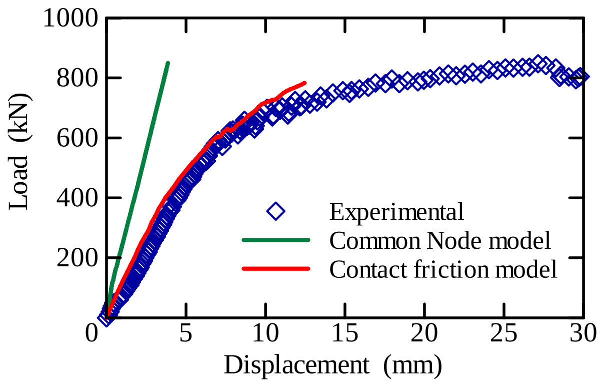


Fig. 2 Load-deflection behavior of sandwiched deck

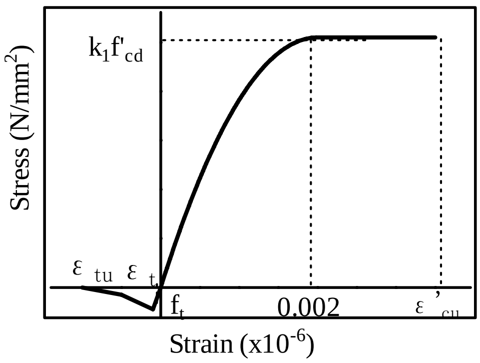


Fig. 3 General constitutive equation (criteria of Japan Society of Civil Engineers[2)])

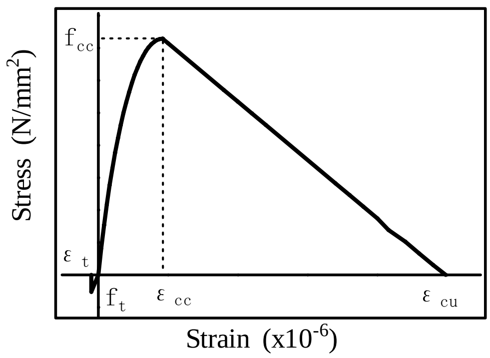


Fig. 4 Constitutive equation for the study deck

2.2 Damage at the site due to the occurrence of a void

A sandwiched deck was designed using a method well reflecting the actual behavior. The pavement was, however, deformed in less than one year after construction. In order to examine the cause, the pavement was removed to investigate the soundness of the deck. Investigations were made at three locations with different degrees of damage to the pavement. The damage to the top steel plate was verified by a liquid penetrant test and the depth of internal void was identified (Table 1).

As a result of the investigation, it was found that radial cracks of 10 to 20 mm occurred at bolted connections on the top steel plate when the depth of the void exceeded 6 mm (Photo. 1). A section with cracks is shown in Photo. 2. A hole was punched on the steel plate in the same shape as that of the circular section above the high strength high nut.

Table 1 Results of field investigation

Location investigated	Depth of void (mm)
With no damage	0.11 ～ 0.30
With damage to the pavement	2.70 ～ 4.90
Serious damage to the pavement and cracking in the top steel plate	6.00 ～

a) Before the removal of the bolt b) After the removal of the bolt

Photo. 1 Cracking in the top steel plate

a) Area around a bolt on the top steel plate b) High strength high Nut

Photo. 2 Condition around a bolt on the top steel plate and shape of the nut

2.4 Reproduction of cracking in the top steel plate[3)]

Cracking was reproduced to examine the cause of damage induced by an internal void. Specimens with a void at a designated position of the deck were used (Table 2). A uniformly distributed load equivalent to B live load (1.0 N/mm^2) was applied to the specimen and a fixed point fatigue test was conducted using a sine wave of 5Hz.

In the case where a bolt was at the center of the void, radial cracks were confirmed on the steel plate at the end of 50,000 times of loading when the depth of the void exceeded 3mm (Photo. 3 a). In the case where the void was between bolts, cracks were confirmed along a tangent to the bolt on the loading side at the end of 100,000 times of loading (Photo. 3 b).

Table 2 List of specimens

Location of void	Dimensions of specimen (mm)	Void (mm)	
		Area	Depth
Surrounding a bolt	900×162×900	600×600	1
			3
			6
Between bolts	900×162×1200	600×900	6

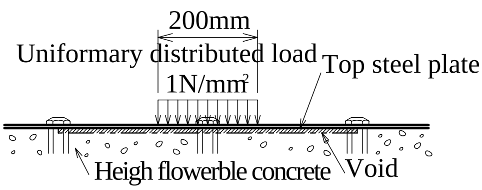


Fig. 5 Model of a void surrounding a bolt

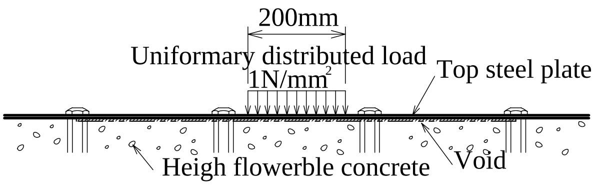
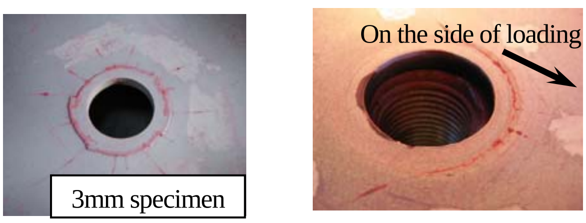


Fig. 6 Model of a void between bolts



a) Void surrounding a bolt b) Void between bolts

Photo. 3 Bolted connection on top steel plate at the end of test

Table 3 List of test results

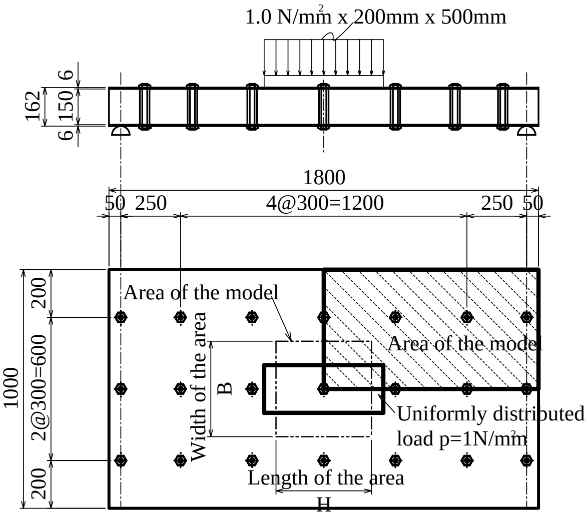
Location of void	Depth of void	Test result
Surrounding a bolt	1mm	No damage incurred at the end of two million times of loading
	3mm	Cracks confirmed at the end of 50,000 times of loading
	6mm	Cracks confirmed at the end of 50,000 times of loading
Between bolts	6mm	Cracks confirmed at the end of 100,000 times of loading

3. Dimensions of void causing damage

The above study revealed that cracks occurred at bolted connections when the depth of the void exceeded 3mm. Actual voids, however, have a varying length, and voids with a certain size may cause no cracking even when the depth of the void exceeds 3mm. Then, the dimensions of the void (area and depth) were examined.

3.1 Analysis model

The model was made of a quarter of the sandwiched deck 1000mm wide, 1800mm long and 162mm thick (Fig. 7 and 8). The model was analyzed in a case with a void at the center of a bolt and another with a void between bolts. The cracks occurring near the connection on the top steel plate were examined.



(in millimeters)

Fig. 7 Model of a void surrounding a bolt

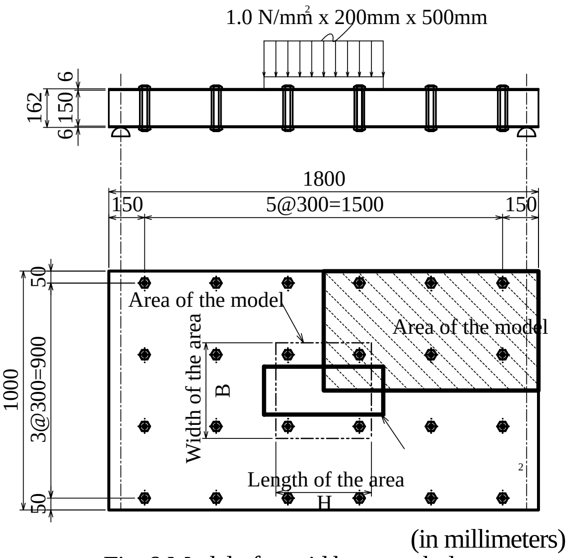


Fig. 8 Model of a void between bolts

All of the elements of the model were of a mean size of 20mm. A radial mesh of 5mm elements was used around the bolted connection with the center of the bolt as the origin. The void was reproduced by removing the elements in the concrete section in the form of a rectangle around the point of loading.

The physical properties of the materials used are listed in Tables 4 and 5. The constitutive equations for respective members are described below. Bilinear type steel was assumed (Fig. 9 a). For concrete, a constitutive equation was assumed based on the one proposed by Hoshikuma et al.4) counting on the restraining by the steel shell cross section in compression. Plain concrete was assumed in tension.

Table 4 Physical properties of Steel materials

	Modulus of elasticity E_s (N/mm^2)	Yield strength f_y (N/mm^2)	Tensile strength f_{cu} (N/mm^2)	Poisson's ratio ν
Steel plates	1.84×10^5	362	487	0.3
Bolt	1.90×10^5	900	1100	0.3

Table 5 Physical properties of Concrete materials

Modulus of elasticity E_c (N/mm^2)	Yield strength f_c (N/mm^2)	Tensile strength f_t (N/mm^2)	Poisson's ratio ν
2.42×10^4	31.7	2.60	0.167

The boundary condition was fixed in each horizontal direction on the sides because of the symmetry of the model, and the support was fixed only vertically. The bolts were fixed to the top and bottom steel plates by an axial force of 220kN. Uniformly distributed monotonic loading (p = 1N/mm^2) was applied at the center of the model (Fig. 7 and 8) in increments in 100 steps.

The nodes between steel plate, concrete and bolts were made independent of one another. A shear model was applied between the nodes while considering the Coulomb friction. The sliding frictional coefficient was set at 0.35 between a steel member (steel plate and bolt) and concrete, and at 0.25 between steel members.

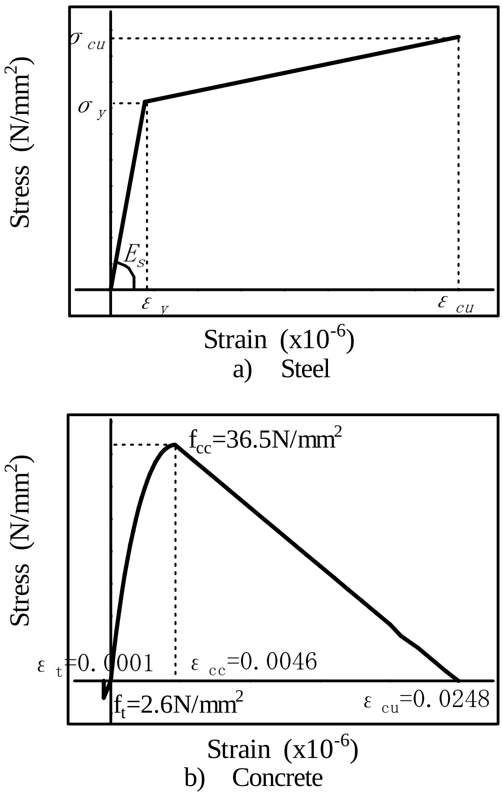


Fig. 9 Constitutive equations for members

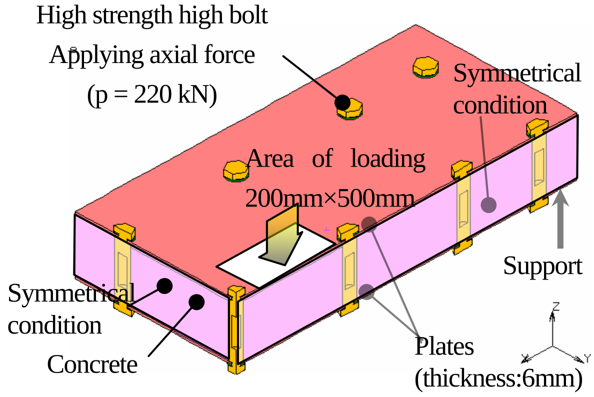


Fig. 10 Analysis model (void surrounding a bolt)

3.2 Effect of the area of void

The distributions of the maximum principal strains from the center of the bolt on the top steel plate were examined at a fixed void depth of 3mm while varying the area of void (Fig. 11 and 12). In the case where a bolt was located at the center of the void, the principal strain was highest near the bolted connection regardless of the area of void. When the void was larger than the spacing between bolts (300mm in this study), strain increased drastically. Strain exceeded a yield strain of 2000$\times 10^{-6}$ when the area of void reached 500mm $\times$ 500mm. The maximum principal strain was smaller in an area of 600mm$\times$600mm probably because of the difference in number of bolts that carried the load due to the relationship between the areas of loading and void.

In the case where the void was located between bolts, the principal strain was largest at a point approximately 50mm from the center of the bolt when the area of the void was smaller than the spacing between bolts. When the area of the void was larger than the spacing between bolts, the principal strain was largest at the bolted connection exceeding the yield strain. This is ascribable to the difference in number of bolts as in the case of the void surrounding a bolt.

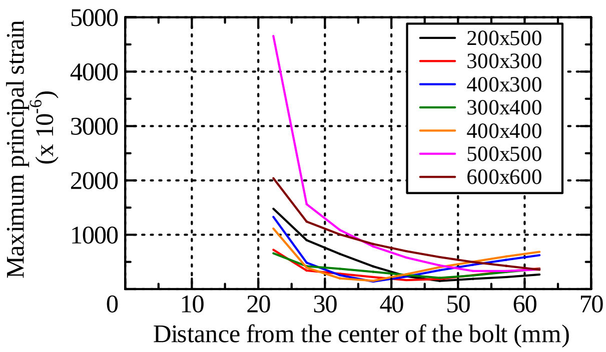


Fig. 11 Distribution of maximum principal strains (loading where the void surrounds a bolt)

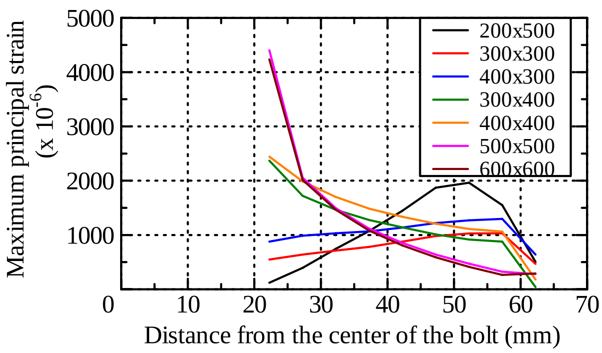
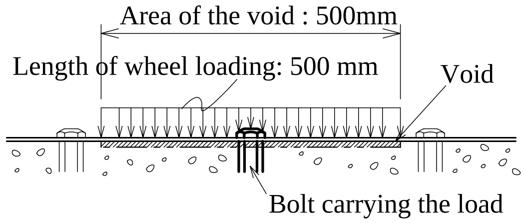
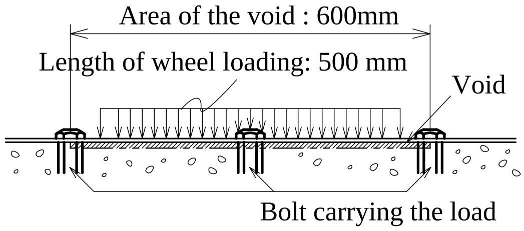


Fig. 12 Distribution of maximum principal strains (loading where the void is between bolts)



a) Case where the area of void is the same as or smaller than the width of wheel loading



b) Case where the area of void is larger than the width of wheel loading

Fig. 13 Area of void and number of bolts carrying the load

3.3 Effect of the depth of void

The discussions in the previous section revealed that the strain at the bolted connection on the top steel plate exceeded the yield strain when the area of void exceeded the spacing between bolts. A comparison was made in the maximum principal strain at the bolted connection on the top steel plate using the parameters listed in Table 6.

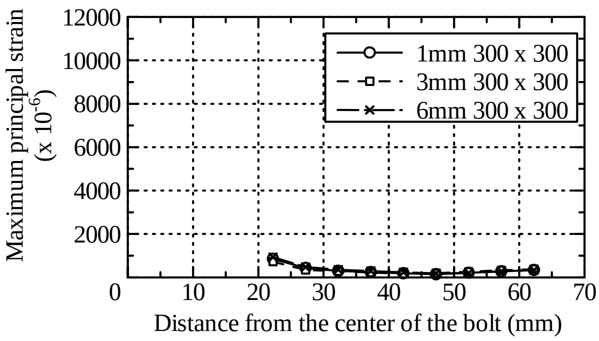
Table 6 Analysis parameters

Depth of void	Area of void B$\times$H(mm)	Location of void
1mm 3mm 6mm	300×300 400×400 600×600	Surrounding a bolt Between bolts

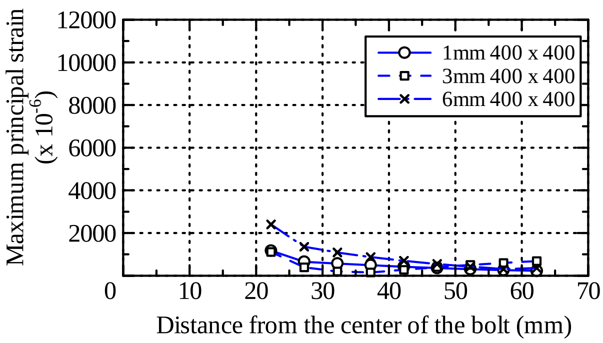
Fig. 14 shows that the strain at the bolted connection on the top steel plate was approximately 1000×10^{-6} where the void surrounding a bolt had an area nearly equivalent to the spacing between bolts and that the deck was usable. No outstanding effect of the depth of void was found where the area of void was 400mm×400mm or smaller. Where the void had an area of 600mm×600mm, the strain was smaller than the yield strain at a depth of 3mm or less. The strain at the bolted connection exceeded the yield strain at a depth of 6mm.

Fig. 15 shows that the strains in the case where the void was between bolts were distributed similarly to the case where the void surrounded a bolt as long as the area of void was nearly the same as the spacing between bolts and that the deck was usable. Where the area of void exceeded the spacing between bolts, however, the strain increased with depth and thus the effect of the depth of void was outstanding.

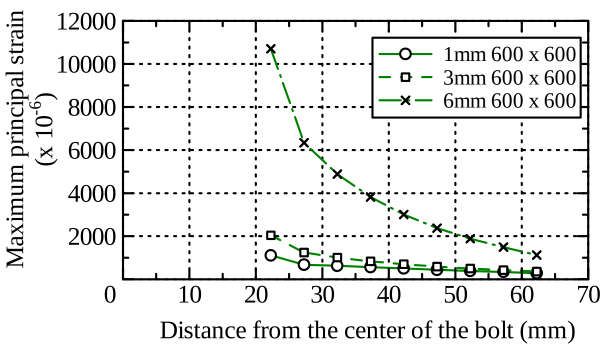
The distribution of strains varied according to the location of the void. The strain increased in proportion to the depth when the area of void exceeded the spacing between bolts in the case where the void was between bolts. In the case where the void surrounded a bolt, the strain never varied in proportion to the depth even when the area of void exceeded the spacing between bolts. When the area of void exceeded the spacing between bolts, two spans were supported by bolts. The span supported by bolts was longer and the steel plate was deformed more where the void was between bolts than where the void surrounded a bolt even if the area of the void was the same. Then, the strain at bolt supports was more outstanding (Fig. 16 and 17).



a) Area of void: 300mm×300mm

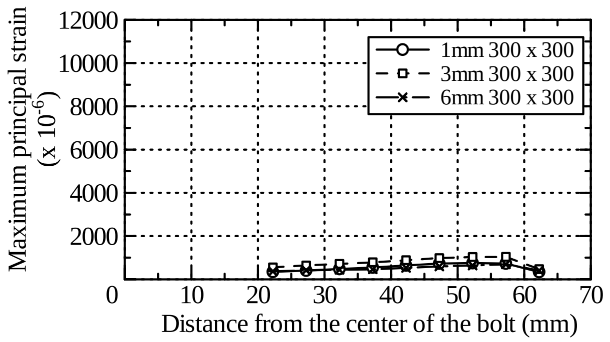


b) Area of void: 400mm×400mm

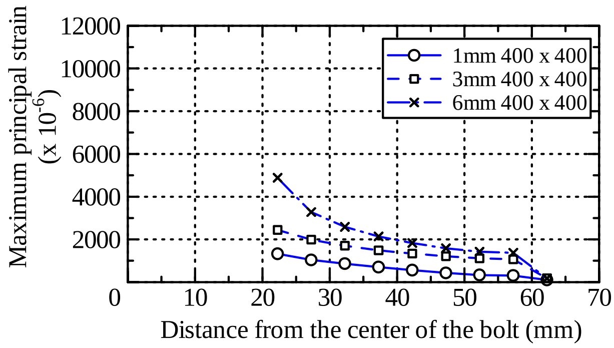


c) Area of void: 600mm×600mm

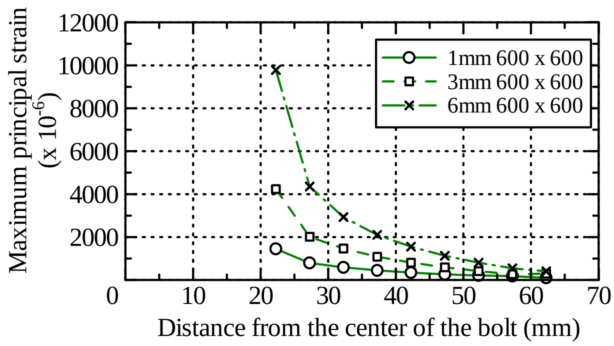
Fig. 14 Distribution of maximum principal strain (void surrounding a bolt)



a) Area of void: 300mm×300mm

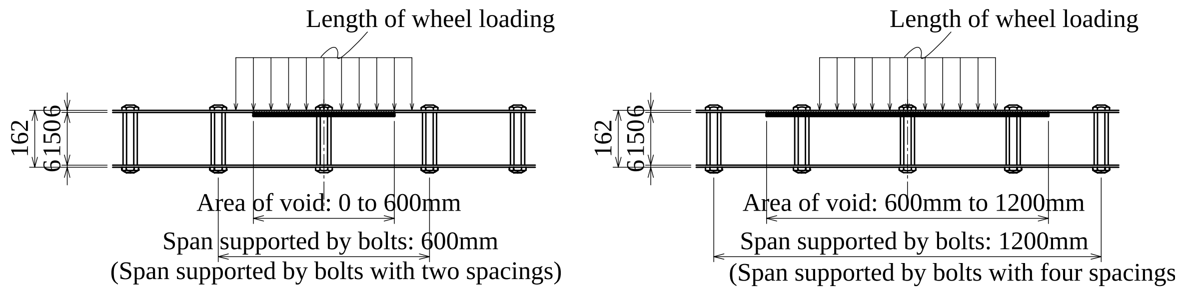


b) Area of void: 400mm×400mm



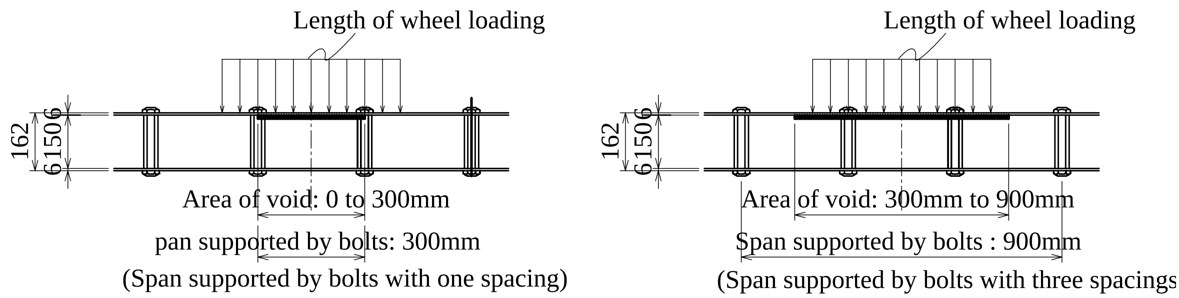
c) Area of void: 600mm×600mm

Fig. 15 Distribution of maximum principal strain (void between bolts)



a) Area of void: Up to 600mm b) Area of void: 600mm to 900mm

Fig. 16 Area of void and span supported by bolts (void surrounding a bolt)



a) Area of void: Up to 300mm b) Area of void: 300mm to 900m

Fig. 17 Area of void and span supported by bolts (void between bolts)

4 Conclusions

As a result of this study, the following conclusions were obtained concerning the cracking at bolted connections on the top steel plate due to the void inside the deck sandwiching concrete with steel plates.

(1) Cracks occurred in the top steel plate when the area of the void exceeded the spacing between bolts and the depth of the void exceeded 3mm.

(2) In the case where the void surrounded a bolt, the strain at the point of loading increased when the area of the void exceeded the spacing between the bolts adjacent to the bolt at the center of the void. The strain was, however, not in proportion to the depth of void.

(3) In the case where the void was located between bolts, the strain increased in proportion to the depth of the void when the area of the void exceeded the spacing between the bolts that carried the load.

(4) The distribution of strains varied greatly according to the spacing between the bolts within the area of the void even if the area did not vary.

As a result, it was found that the cracking in the top steel plate was closely related to the point of wheel loading, and the depth and area of the void. Identifying the relationship between the area of void and the positions of bolts is considered important because the strain near the bolted connection on the top steel plate increased drastically when the area of void exceeded the spacing between bolts that carried the load.

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