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Joint Displacement Resistance Evaluation of Waterproofing Material in Railroad Bridge Deck

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철도교량상판 방수재료 선정을 위한 균열거동저항 성능평가

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Abstract A joint displacement resistance evaluation method for selecting waterproofing materials in railway bridge decks is proposed. The displacement range for an evaluation is determined by finite element method (FEM) analysis of a load case based on an existing high-speed PSC Girder Box railroad bridge structure. The FEM analysis results were used to calculate the minimum joint displacement range to be applied during testing (approximately 1.5 mm). For the evaluation, four commonly used waterproofing membrane types, cementitious slurry coating (CSC), polyurethane coating system (PCS), self-adhesive asphalt sheet (SAS), and composite asphalt sheet (CAS), were tested, with five specimens of each membrane type. The joint displacement width range conditions, including the minimum displacement range obtained from FEM analysis, were set to be the incrementing interval, from 1.5, 3.0, 4.5, and 6.0 mm. The proposal for the evaluation criteria and the specimen test results demonstrated how the evaluation method is important for the sustainability of high-speed railway bridges.

요 약 본 논문에서는 철도교량상판에 적용하는 방수재료 선정을 위한 이음부 및 균열부에 대한 거동 저항 성능평가를 수행하였다. PSC거더 철도 교량상판에서 발생하는 일반적인 변위 범위 조건을 도출하여, 도출한 결과에 따라서 방수재료의 균열 거동 저항 성능평가 방법을 개발하였다. 재안하고자 하는 평가를 위한 균열거동폭 (mm)을 설정하기 위해 레일도상이 설치되어있는 PSC 거더 교량을 대상으로 유한요소 모델링 해석을 수행하였으며, 최소 균열 거동 범위 (약 1.5mm)를 도출하였다. 평가 방법으로서는 교량 상판에 통상적으로 사용되는 시멘트계 도막 시스템, 폴리우레탄 코팅, 접착식 아스팔트 시트 및 합성 고무 겔 복합 아스팔트 시트 시스템 총 4가지 종류의 방수재료를 선정하여, 각 방수재료 종류별 5가지의 시편을 제조하여 성능 평가를 수행하였다. 각 시험편별로 4가지의 균열 거동폭조건 (1.5, 3.0, 4.5, 6.0mm)에 대해 평가를 수행하였으며, 본 연구를 통하여 철도교량에 일반적인 균열 거동 폭을 고려한 평가 기준에 따라 각 방수재료별 누수저항성 평가에 따른 철도교량상판 사용 적합성을 판단하였다.

Keywords : Railway Bridge Deck, Waterproofing Membrane, Joint Displacement, New Evaluation Method, Finite Element Method Analysis, Bending Stress

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1. Introduction

Waterproofing membranes must be able to maintain adhesion on to the concrete surface and prevent the formation of leakage path through joint or crack into the reinforced concrete deck section, but there is currently no existing method that can accomplish this evaluation. Therefore, this study proposes a joint displacement resistance performance of waterproofing systems, and provide an evaluation method, criteria, and demonstration that is suitable for high-speed railroad concrete bridges. The study outlines the existing evaluation methods for waterproofing systems and compared to discuss the lack of joint displacement resistance performance test method. Next, the degradation conditions of a high-speed double-track railroad bridge structure deck is analyzed through FEM and analysis of existing stress factors to propose the requirement for setting the minimum displacement range to be used during testing. Based on these findings and analysis, a new evaluation method is proposed specifically to evaluate the resistance performance of waterproofing materials against joint displacement on railroad bridge decks.

1.1 Background

Waterproofing membranes are installed between the track bed and the concrete deck substrate [1]. Waterproofing installation in a pre-stressed concrete (PSC) bridge girder based railroad bridge structure is shown below. The PSC bridge girder is based on a model of an existing bridge in Korea.

While the slab thickness of the bridge deck is different depending on the bridge type, the PSC girder box construction specification in Korea states a height of 3.5~4 m, and the composition of the track bed about 1 m in thickness comprised of ballast layer (t:300 ~350 mm) beneath the sleepers, ballast mat (t: 100 ~ 150 mm), protection concrete (t:300 ~ 400 mm) and waterproofing layer (t: 2 ~ 4 mm). at the cross-sectional structure of the high-speed rail bridge, the bridge deck can be divided into two parts: track and sidewalk [2]. Depending on the design standard, a water flow drainage system is installed at the respective sides of the track bed.

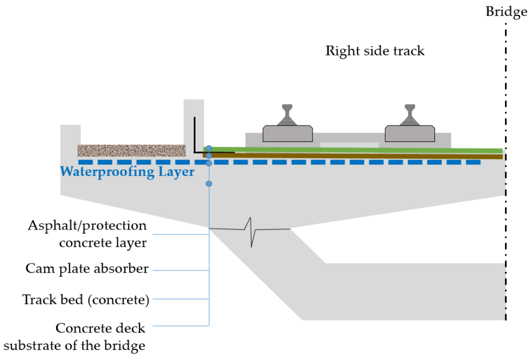


Fig. 1. Sample PSC track bed structure design layout with waterproofing system

Based on existing studies and reference materials, a generalized classification can be drafted [3]. Representative waterproofing systems for bridges can be comprised of 1) sheet membrane system, 2) spray or liquid applied membrane system, and 3) cementitious slurry membrane system [4]. A series of simplified illustration of the waterproofing system schematic on railroad bridge decks is outlined in Table 1 shows the waterproofing systems used by respective nations/regions in the world;

Table 1. Representative classification of waterproofing systems for railroad bridge deck in international application

Nations	Waterproofing materials and types		
	Sheet membrane system	Liquid Applied membrane system	Cement membrane system
U.S.	0	0	X
European Nations	0	0	X
Japan	0	0	X
Korea	0	0	0
China	0	0	0

1.2 Conventional loading conditions in railway bridge tracks

When only considering train load and subsequent repair works the load from the train does not transfer to the waterproofing layer to a significant degree [5]. Recent assessment report result in Korea on the effect of load on the waterproofing layer installed in a PSC box railroad bridge shows that under normal circumstances, the maximum stress generated at the waterproofing membrane installed 1 m below the track bed is 0.28 Mpa under thermal loading [6]. However, conventional FEM modelling conditions only considers the load from the train and the thermal load on the concrete deck. A detailed analysis of the joint displacement resistance performance (crack bridging) while under the simultaneous degradation effect of thermal loading and load from passing train has not been performed. To propose an appropriate evaluation method, the exact degradation mechanism in the railroad bridge structure must be outlined.

1.3 Thermal stress and temperature variation effect to joint displacement

When concrete is subjected to external stress, the concrete matrix is subjected to elastic strain followed by a time-dependent increase in strain. For example, drying shrinkage occurs in most structural elements stored at usual temperature and relative humidity [7]. To calculate the deformation and deflection of structural members due to thermal stress, the relation between stress and strain is required. For most concrete materials this relation between thermal stress/strain and deformation is expressed by the coefficient of thermal expansion (equal to approximately 9.8 × 10-6 per °C for concrete structures) and the change in temperature in °C [8]. Thermal deformation is expressed by linear expansion coefficient α, and is defined by the following equation;

$$\alpha = \frac{\triangle L}{L \times \triangle t} \tag{1}$$

As shown in Table 3, the road surface of the bridge shows various temperature characteristics under the ambient temperature of -20 ~ 30 ℃ throughout the different seasonal conditions. If the air temperature is 30 ℃, the temperature of the deck surface can rise up to 55 ℃ during summer time. In the case of Korea, the temperature difference between day time and night can reach as much as 20 ℃ many thermal expansions are expected [9]. Based on sample calculation results, the expected concrete expansion can reach up to approximately 1.176× 10-2 m.

1.4 Bending moment and shear stress effect on crack displacement

When under dynamic load of a high speed train, the structure undergoes a bending moment, thereby applying shear force onto the railroad bridge. Typical high-speed railroad operation speed reaches 200~300 km/h, and Korean train dynamic load averages between 75~120kN/mm2 [10]. To propose the displacement conditions, the bending moment and stress conditions applied to the waterproofing membrane and the concrete bridge deck due to the train operation dynamic load was analyzed through FEM using a MIDAS analysis program. In the analysis, a case of a double-track bridge is modelled the dynamic responses of only one track is investigated and the other track is considered to be the dead load of the bridge, because the flexural rigidity of the bridge is usually thousands of times greater than that of the rails (or even tens of thousands).

2. Test Method

2.1 3D Modelling Process Proposal for displacement range parameter

The proposed 3D coupling element consists of several rail elements of equal lengths (including the left and right rail), a bridge element, a few sleepers, a series of fasteners, and a series of discrete ballasts. It can also include a bearing that connects a pier node at a supporting point of the bridge. The rails, bridges, and piers are modeled as uniform beams, while each sleeper is modeled as a rigid body, and the lateral and vertical elasticity and damping properties of the fastener, ballast, and bearing are modeled as springs and dampers. The parameters for the analysis is outlined in Table 2, and illustration of the analysis is shown in Figure 2. below;

Table 2. FEM analysis parameters and conditions

Analysis condition	Value
Train type (dynamic load)	KTX (Axial load: 17 tons)
Operation speed	300 km/h
Bridge length	10 m
Bridge width	6 m
Gauge length	1,435 mm
Rail mass	60 kg (Specification: KSCE-LSD15(S))
Waterproofing material analyzed	Asphalt sheet system
Track type	Concrete (Specification: KSCE-LSD15(RC))

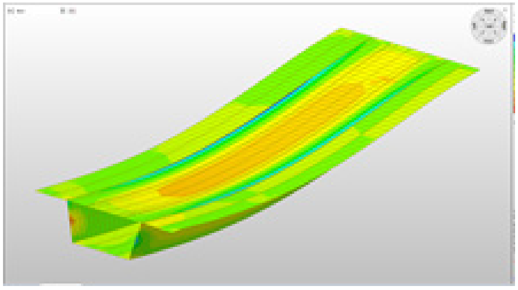


Fig. 2. FEM analysis of the load conditions of waterproofing membrane and concrete railroad bridge deck

First, a PSC bridge structure is modelled , and a time history function of the dynamic load case is applied to the double-track rails and the stress-deformation analysis is derived . Next, the deformation results are isolated for the waterproofing layer and the concrete bridge deck, where upon the stress measured on the waterproofing layer was very minimal (0.22 MPa), and the waterproofing layer should be designed to respond to the stress deformation of the concrete bridge deck as it is an adhered surface to the concrete surface. Based on the analysis results, maximum displacement of approximately 5.415×10^{-2} m concrete deck displacement is expected.

2.2 Proposed Joint Displacement Test methodology

In order to conduct a joint displacement evaluation method, a specimen has to be constructed such that a waterproofing membrane can be installed over a set of concrete/mortar substrate slabs with an artificial crack or joint. As cracks are difficult to simulate with consistent depth and width variables, for this testing demonstration, the displacement simulation condition was set compliant to joint conditions only.

For the testing, the specimen is comprised of upper and lower mortar substrate parts. The two substrate are placed together at the cross section interface, wherein forming a concrete joint. The waterproofing membrane is installed over substrate surface, completely covering the concrete joint.

The substrate parts are mixed at water to cement to sand ratio of 0.4:1:3, during the mortar casting, threaded conduit parts are placed in their corresponding substrate parts which will be used for connection to the testing device. During casting in the molds, rod tamping is conducted to remove air voids. The freshly cast mortar is cured in a standard laboratory setting for 3 days in ambient conditions (temperature of 20 ± 3 ℃ and relative humidity of 60 ± 3 %). Plastic vinyl sheets should be used to cover the molds while curing to prevent evaporation. The threaded conduit installed at the lower mortar substrate serves two functions where the part is used to connect to the UTM device for testing, and acts as an outlet for leakage during joint displacement testing. In this regard, the point of leakage occurrence can be checked immediately during joint displacement.

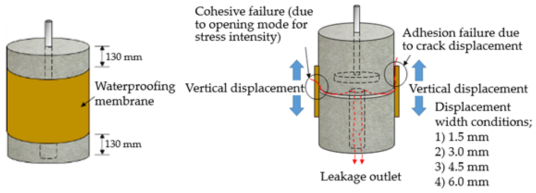
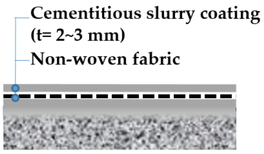
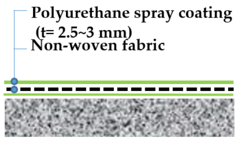
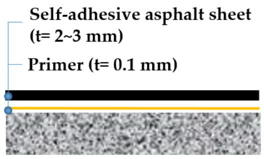
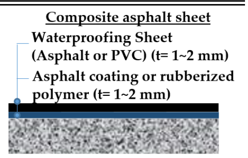


Fig. 3. Crack displacement testing specimen

For this testing, 4 types of waterproofing systems were selected; 1) Cementitious slurry coating (CSC) in cementitious membrane system, 2) polyurethane spray coating (PUC) in liquid applied membrane system, 3) self-adhesive asphalt sheet (SAS) in asphalt sheet system, and 4) Composite asphalt sheet (CAS) in asphalt sheet system. Waterproofing systems are all compliant to the material specifications under KS F 4917 and KS F 4934. Refer to Table 6 below for details and illustration of waterproofing layers used in this study;

Table 3. Types of waterproofing membranes evaluated

Cementitious slurry coating (CSC)	Polyurethane spray coating (PUC)
	
Self-adhesive asphalt sheet (SAS)	Composite asphalt sheet (CAS)
	

For the cementitious slurry coating (CSC), the non-woven fabric sheet is installed onto the mortar substrates, and a fabric layer is impregnated with the cementitious slurry coating material with 2 ~ 3 mm thickness. The installed specimens are allowed to cure in accordance to the manufacturer specifications.

For the polyurethane spray coating (PUC), the non-woven fabric sheet is installed onto the mortar substrates, and a fabric layer is impregnated with the polyurethane spray coating material with 2 ~ 3 mm thickness. The installed specimens are allowed to cure in accordance to the manufacturer specifications.

For the self-adhesive asphalt sheet (SAS), the membrane is cut into a 650 by 150 mm rectangular piece. The membrane is installed on the mortar substrates placed together with the short dimension applied perpendicular to the joint gap. When applying the waterproofing membrane sheets, an overlap joint with a minimum width of 30 ~ 50 mm is made.

For the composite asphalt sheet (CAS), the composite membrane is first installed onto the mortar substrates with a minimum thickness of about 1 ~ 2 mm. the sheet component is also cut into a 650 by 150 mm rectangular piece. The membrane is installed on the mortar substrates placed together with the short dimension applied perpendicular to the joint gap. When applying the waterproofing membrane sheets, an overlap joint with a minimum width of 30 ~ 50 mm is made.

For this proposed test method, the concrete deck joint displacement range are used as a reference to establish the minimum displacement range for the testing. While the analysis data can approximate the minimal displacement conditions based on reference analysis of thermal deformation and elastic deformation of concrete, the realistic concrete deformation can reach higher ranges depending on the size of the joint width, and the waterproofing membrane should be able to withstand the deformation conditions at any given realistic range.

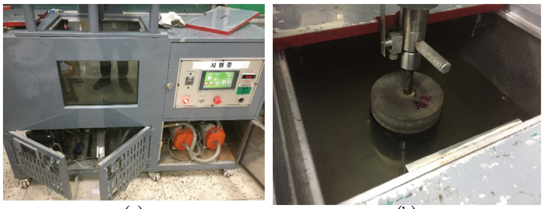
The displacement load width range was divided into 4 different widths to ensure that the results take into account various types of displacement conditions under maximum loading conditions in consideration of environmental and dynamic loads in railroad concrete bridges. Refer to Table 4 for the joint displacement ranges.

Table 4. Displacement range for joint displacement testing

Displacement Range Description	
1.5 mm	Minimum joint crack displacement range of normal PSC substrate of 10 m span (in consideration of (Equation (1), (2), and (3) on the FEM modelling results).
3.0 mm	Average joint displacement range of normal PSC substrate of 10 m span. Joints of at least 1.5 mm width and 10~15 mm depth will be subject to this range of displacement when thermal stress deformation and bending moment due to train wheel load is considered.
4.5 mm	High joint displacement range of normal PSC substrate of 10 m span. Joints of at least 2.0 mm width and 15~20 mm depth will be subject to this range of displacement when thermal stress deformation and bending moment due to train wheel load is considered.
6.0 mm	Extreme joint displacement range of normal PSC substrate of 10 m span. Joints of above 2.5 mm width and 20~25 mm depth will be subject to this range of displacement when thermal stress deformation and bending moment due to train wheel load is considered.

2.3 Testing apparatus design and specimens setting for joint displacement evaluation

The apparatus consists of a joint displacement simulation chamber that can automatically fill the chamber with water during joint displacement testing. The waterproofing membrane specimen is first secured in the water chamber (or apparatus) by the threaded conduit, which is then filled with water approximately 10 ~ 15 L of water such that the specimen is completely submerged in water, and inserted into the water chamber for displacement load testing. Once installed, the upper substrate is subject to vertical tensile motion in relation to the bottom substrate fixed to the apparatus, thereby simulating a joint displacement stress by 4 displacement ranges on the installed waterproofing specimen. Refer to Figure 4 for details.



(a) (b)

Fig. 4. Testing apparatus illustrated (a) Overview of the joint displacement simulation water chamber; (b) Specimen installed in the joint displacement simulation water chamber

The joint displacement speed (construction joint displacement rate) is set to 50 mm/min. The final evaluation for the joint displacement testing for each specimen is determined by the total number of displacement (displacement = 1 complete motion of vertical up and down displacement) resisted until leakage occurs.

3. Results and Discussion

The number of displacement cycle resisted until leakage which the evaluation results of 5 specimens response to 4 width ranges (1.5, 3.0, 4.5 and 6.0 mm) of joint displacement for the 4 respective waterproofing systems (CSC, PUC, SAS and CAS) are shown.

The results are displayed in the following Tables 5 to 8, where the results show that the performance of the waterproofing membranes decreases marginally as the displacement width increases.

Table 5. CSC Evaluation Results

Displacement Ranges	CSC Results (Specimens)				
(mm)	1	2	3	4	5
1.5	387	421	367	413	356
3.0	98	106	59	121	76
4.5	7	4	6	12	8
6.0	3	5	4	6	8

Table 6. PUC Evaluation Results

Displacement Ranges	PUC Results (Specimens)				
(mm)	1	2	3	4	5
1.5	468	641	523	578	463
3.0	437	237	517	463	503
4.5	37	42	20	51	19
6.0	5	4	6	4	3

Table 7. SAS Evaluation Results

Displacement Ranges	SAS Results (Specimens)				
(mm)	1	2	3	4	5
1.5	527	582	423	574	451
3.0	542	498	474	536	542
4.5	571	437	421	550	409
6.0	329	442	524	349	404

Table 8. CAS Evaluation Results

Displacement Ranges	CAS Results (Specimens)				
(mm)	1	2	3	4	5
1.5	712	736	681	625	731
3.0	762	439	726	521	782
4.5	746	647	673	742	690
6.0	582	734	627	739	705

In the case of the results for 1.5 mm, all of the waterproofing system types were able to resist the joint displacement to a high degree (from approximately 300~700 displacement cycles), indicating that when joint displacement of minimal range is expected in a railroad bridge structure in accordance to the given environment and the joint condition, any type of the waterproofing systems can be used. However, as the displacement range increases from 3.0 mm to 6.0 mm, it is shown that there is a general trend of decreasing performance, and a more careful selection process of the waterproofing membrane should be conducted. Using the existing evaluation methods for waterproofing membranes has not able to approximate the waterproofing performance with regard to joint or concrete displacement resistance, and these results demonstrate that the conditions of the PSC railroad structure joint width, depth and expected displacement range must be considered during the selection of waterproofing membranes during design and construction.

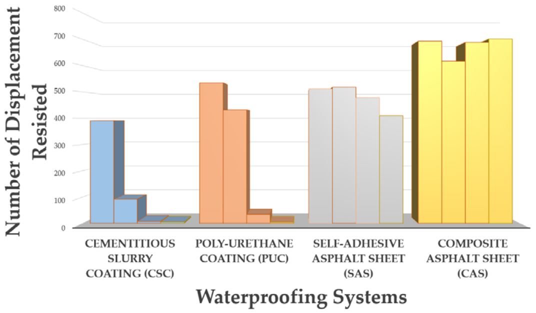


Fig. 5. Joint displacement resistance performance result of the respective waterproofing system types (Per waterproofing system type)

In Figure 5, in this study the results indicate that CSC and PUC types in particular do not have high relative displacement resistance performance than the SAS and CAS types, and CSC type can be used in bridge structure where barely any joint displacement conditions are expected and only the stress deformation due to bending moment and thermal stress deformation are the factors for displacement. In contrast, the PUC has minimal joint displacement resistance performance (moderate performance can be expected only up to 3.0 mm), but both the CSC and PUC types cannot be expected to have a long life cycle performance against joint displacement (for the CSC, maximum of up to 391 cycles, and for PUC, maximum of up to 534 cycles for 1.5 mm and 431 for 3.0 mm displacement widths). For both the SAS and CAS type, it can be said that SAS types has a moderate resistance performance against joint displacement of all width conditions (from 410 to 518 cycles), whereas for the CAS type, has a high resistance performance against joint displacement of all width conditions (from 617 to 701 cycles) than another 3 types of waterproofing system. Based on the current demonstration results the following table of evaluation regime and the grading system) for the waterproofing membrane joint displacement resistance testing can be proposed.

3.1 Stress distribution analysis of each waterproofing membrane types

The results analyzed and the leakage causes from the testing underlines that each waterproofing membrane types have different response limit to the joint displacement. The following figure shows the type of stress resistance factor that waterproofing membranes must respond to in bridge sections;

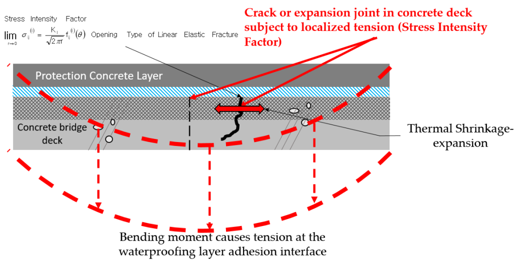


Fig. 6. Stress factors of a bridge deck

As can be seen in the following figure, CAS types (cementitious capillary systems) have low modulus of elasticity, and the stress applied near the crack is higher. With the PUC types (polyurethane coating) the stress distribution is more minimal, whereas for the SAS and CAS types (sheet types), the stress distribution is more even. This indicates that railway bridges should prioritize using sheet types over the other conventional waterproofing membrane types.

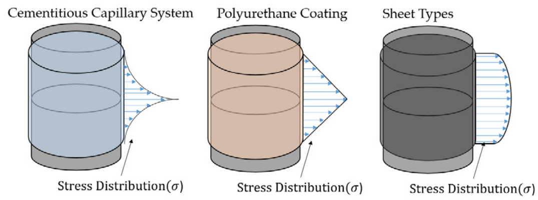


Fig. 7. Stress distribution image of the waterproofing membrane types

3.2 Grading system proposal based on evaluation method result

The demonstration of the evaluation method shows it is shown that there is a general trend of decreasing performance, and a more careful selection process of the waterproofing membrane should be conducted. In the proposed example grading system, only the displacement width range is considered as part of the evaluation criteria as a correlative analysis on the maximum number of displacement cycles resisted and joint resistance performance index is not yet been made clear. One cycle can represent a durability duration factor of 1 day or 1 year depending on requirements of the bridge structure. Nevertheless the proposed evaluation regime is a step towards an improvement on the practical assessment of waterproofing material performance, because the existing evaluation methods for waterproofing membranes has not been able to approximate the waterproofing performance with regard to joint or concrete displacement resistance. Based on the grading criteria, CAS would apply to the excellent resistance capacity grade as their resistance results were the highest over the other types of waterproofing membranes tested, and SAS would apply to the High resistance capacity grade. PUC would apply to the moderate resistance capacity, with the CSC following as the minimal resistance capacity grade. This grading system can be included in the existing standard design guidelines for railway bridge deck construction, and used as a guideline for selecting future waterproofing membrane types applicable to railway bridge structures in future construction.

Table 9. Grading Criteria

Grade	Description
Minimal resistance capacity grade:	Materials such as cementitious slurry system, capable of handling up to 1.5 mm displacement range but no higher to ensure long term durability. can be used in; low expectation of environmental degradation factors, and cracks will not occur.
Moderate resistance capacity grade	Materials such as polyurethane coating, capable of handling up to 3.0 mm displacement range but no higher. can be used in; short span bridge structures (approximately 10 m), low expectation of environmental degradation factors and mins may occur.
High resistance capacity grade	Materials such as self-adhesive sheets, capable of handling up to 4.5 mm displacement range. can be used in; moderate length bridge structures (<15m, >10 m), environmental degradation factors can occur, cracks may occur naturally
Excellent resistance capacity grade	Materials such as self-adhesive sheets, capable of handling up to 4.5 mm displacement range. can be used in; most bridge structures (>10 m), environmental degradation factors can occur, extreme cracking may occur naturally

4. Conclusion

In this study, a joint displacement resistance evaluation method of different waterproofing systems (membranes or materials) is proposed, with the results of which an optimal waterproofing system can be selected that comply to the joint displacement degradation conditions of high-speed railroad bridge decks. The study offers the following conclusions;

The displacement range to be used for the testing was determined based on the reference materials on 1) typical thermal stress deformation conditions of PSC deck used in railroad bridges and 2) concrete deformation due to the wheel load of train operation. While the minimum displacement range can be derived based on the modelling of a typical railroad bridge structure, a precise estimation of joint displacement on the bridge deck is difficult as the displacement range heavily depends on the size of the joint . In this regard, the demonstration of the evaluation method in this study proposes various ranges of joint displacement (from 1.5 mm, minimum, to 6.0 mm, extreme, ranges) to clearly compare the displacement resistance performance of different waterproofing systems (CSC, PUC, SAS and CAS). Furthermore, the stress distribution analysis for the waterproofing membranes based on the joint displacement resistance result shows that for bridge types, SAS and CAS types should be prioritized for usage over the CSC and PUC types.

The proposed joint displacement resistance performance testing in this study is one such that can evaluate the respective performance of different waterproofing membranes based on changing joint displacement width. It is too early to derive conclusive statements using only the results from the demonstration evaluation conducted in this study, but this demonstration was able to outline which waterproofing system has the highest relative joint displacement resistance performance.

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