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Technical Report

Lineup of Composite Segments with Special Fitting Joints to Achieve Safe and Highly Durable Shield Tunnels

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Abstract

In view of the long service life of shield tunnels, ensuring security against unexpected earthquakes and increasing the durability of segments are paramount. To meet these needs, Nippon Steel Corporation has developed and marketed the NM Segment, a composite segment with special fitting joints for large-diameter tunnels. The NM Segment has received a favorable reputation in the market for its high seismic resistance and water sealing performance due to its unique fitting joints. However, it cannot be applied to small diameter tunnels due to manufacturing constraints. To overcome this limitation, we have developed a new composite segment with special fitting joints "NMW" for small diameter tunnels. This paper reports on the features of this composite segment lineup and the results of structural laboratory tests of NMW.

1. Introduction

Generally, the underground structures represented by tunnels are prone to follow ground deformation caused by an earthquake and are considered to be excellent in seismic resistance. In addition, the development of tunneling technologies after the 1990s has been remarkable, which has decreased the number of initial failures such as cracks and water leakage. As a result, the quality of tunnels right after the completion of construction has been greatly enhanced. However, in the Kumamoto Earthquake that occurred in 2016, the Tawarayama tunnel (NATM construction method applied) suffered from major damage exceeding assumptions, in which the tunnel lining collapsed on a large scale.[1] Furthermore, in the metropolitan area highway Haneda tunnel (wherein the open cut construction method and submerged tunneling construction method were employed), the occurrence of significant water leakage and deterioration of component members have become apparent, requiring drastic improvement and repair.[2] In addition, there is a report[3] that the corrosion of the skin plate of steel segments has progressed at a rate greatly exceeding assumptions, and caused water leakage in the tunnel.

Thus, damages and deterioration beyond assumptions made at the planning and design stages have occurred in many tunnels, and these not only have the possibility of increasing the tunnel maintenance costs but also suggest the possibility of directly affecting human lives. Besides aiming at further long-term use of tunnels, there are strong needs to secure relief and safety in the event of probable earthquake damage beyond assumptions and to extend the durability of tunnels which are more difficult to repair than aboveground structures. This paper reports the lineup of the composite segments with special fitting joints for shield tunnels developed to meet these requirements.

2. Features and Effects of Composite Segments with Special Fitting Joints

2.1 Features

Nippon Steel Corporation has developed the "NM segment™", a composite segment with special fitting joints, and it has been marketed since its application to the Osaka Pref. Neyagawa Kita underground river "Furukawa detention pond" (1996–1997), and up to the present year of 2022, it has been employed for more than twelve tunnels mainly in underground rivers, underground railways, and road tunnels. The most important characteristic of the NM segment™ is the specially shaped steel having a grooved fitting mechanism structure which acts as the main girder of the steel shell covering the outer surface (**Fig. 1**). The specially shaped steel becomes a

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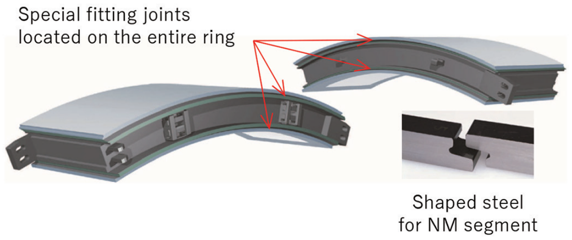
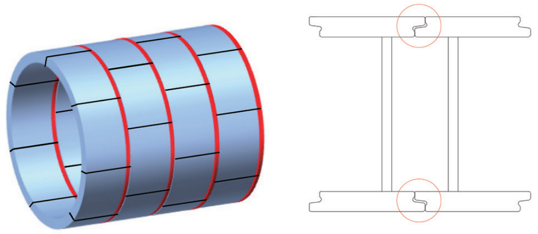


Fig. 1 NM segment

Fig. 2 Predicted damage of tunnel by earthquake


(a)
Special fitting joints
located on the entire ring
(circumferential joint)

(b)
Fitting detail

Fig. 3 Special fitting joints

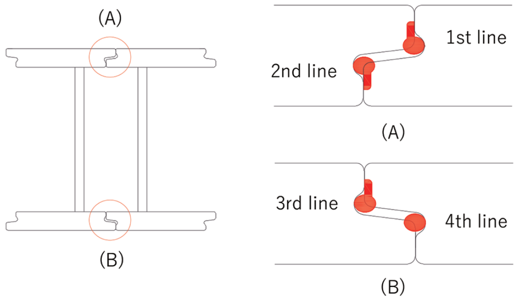


Fig. 4 4 sealing lines of NM segment

joint structure fitting the neighboring rings along the entire circumference upon assembly as a tunnel. In addition, the fitting groove bottom can store waterproof rubber of specific configuration, and when in use, four water-sealing lines in total are formed on the ground side and on the inner space side.

2.2 Seismic resistance performance

A shield tunnel connected to a number of joints is advantageous in that it is prone to following the ground deformation caused by an earthquake. On the other hand, in the case that, for example, the circumferential joints are damaged due to an excessive deformation caused by an earthquake beyond assumption, some of the rings may become isolated, and under the condition where the state of constraints of the ground becomes unpredictable due to earthquake, the tunnel structure could become very unstable, resembling that of a multi-hinged structure. In such a case, depending on the state of tunnel deformation and/or the state of the damage of the longitudinal joints, the highly risky fall of segment pieces that directly endanger human lives may be caused on a large scale (**Fig. 2**).

Contrarily, the circumferential joint structure of the NM segment™ fitted to each ring along the entire circumference can be considered as a high-strength circumferential joint since it disperses the shearing force acting between rings (**Fig. 3**). Thus, even in an unprecedented earthquake, the circumferential connection is sustained, suppressing the occurrence of a serious accident like the fall of segment pieces.

2.3 Durability performance

Generally, the deterioration phenomenon of tunnels is considered to be mainly caused by water leakage into the tunnel, most of which takes place at the joint section. The water-sealing performance of joints is secured by attaching waterproof rubber to the joint, and globally, one line of an ethylene-propylene rubber (EPDM) gasket is used in general. In Japan, generally, two lines of water-swelling type rubber are used in large diameter tunnels.

In this regard, the characteristic four sealing lines of the NM segment™ using water-swelling type rubber (**Fig. 4**) exert extremely high water-sealing performance. In the aforementioned Furukawa detention pond, water leakage has scarcely occurred in the entire 25 years since its start of service. In other employed cases as well, together with the waterproofing function of the steel shell structure of the segment, the actual results of the extremely high water-sealing performance of nearly zero water leakage have been confirmed. Furthermore, since there is no water leakage inside the tunnel, the corroding environment in the tunnel is considered to closely resemble the design stage assumptions, and therefore, the deterioration of the tunnel component members due to corrosion remains within assumptions.

3. Development of Composite Segments NMW™ with New Fitting Method

3.1 Development of NMW™ and its features

Although the NM segment™ has excellent seismic resistance and durability, due to constraints in the manufacturing of its component members such as the specially shaped steel, its application has been limited only to the large-diameter tunnels with an outer diameter of approximately seven meters or larger. On the other hand, to counter the spate of downpours, the needs for exploiting underground space not only in the big cities like Tokyo or Osaka, but also in local governments, are increasing. However, these tunnels are of a small diameter comparatively, and the application of the NM segment™ has been difficult.

To solve this problem, in 2021, Nippon Steel developed new composite segments with special fitting joints "NMW™" for medium diameter tunnels. NMW™ employs new section steel as the main girder having the same fitting structure as that of the NM segments. This alleviates the constraints in manufacturing its component members by simplifying the structure (**Fig. 5**). Furthermore, the newly developed dumbbell joint is employed as the longitudinal joint of NMW™, which can directly transfer the tension force on

Fig. 5 NMW segment

(a) "Dumbbell" joint (M)

(b) "Dumbbell" joint (after fitting)

Photo 1 Longitudinal joint of NMW

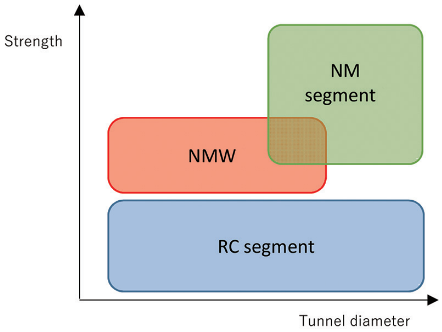


Fig. 6 Application of NMW

the joint to the main girder, and can also save labor at the construction site as well (**Photo 1**).

Due to this development, the same seismic resistance and durability as that of the NM segment™ can be provided to medium diameter tunnels, and with the lineup of the two products, the application range of composite segments with special fitting joints could be expanded (**Fig. 6**). The results of the experiments verifying the performance of the segment main body and the longitudinal joint of NMW™ are reported hereunder.

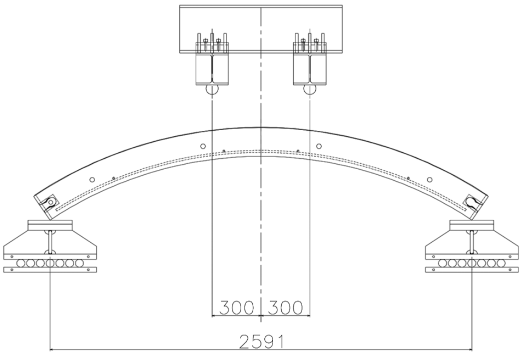
3.2 Performance of the main body of NMW™

3.2.1 Test method

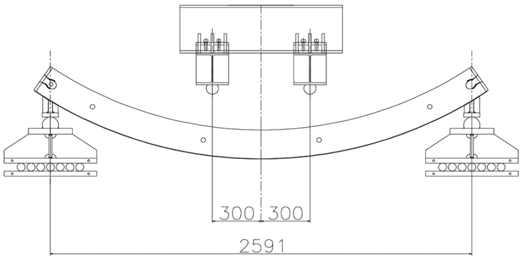
In order to verify the load bearing performance of the main body of NMW™, two bending tests of a main body were conducted. In the tests, four-point bending loading was supplied for positive bending moment and negative bending moment using a circular-arc shape test specimens. The outline of the test is shown in **Fig. 7**, and the outline of the test piece is shown in **Fig. 8** and **Table 1**.

3.2.2 Structural model

For the structural analysis of NMW™, a model of an RC section was employed based on the assumption that the main girder is replaced with a reinforcing bar and only the compression side of the packed concrete effectively works on the entire width. Such model is hereafter referred to as the "main body structural model." In this test, the material strength put into the main body structural model employs the actual values obtained from the results of the material test. The material strength is shown in **Table 2**.



(a) Positive bending test



(b) Negative bending test

Fig. 7 Bending test of NMW

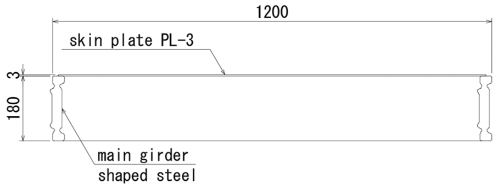


Fig. 8 Cross-section of NMW

Table 1 Specification of NMW test specimen

Width	1200 mm
Height	183 mm
Main girder	27 mm (thickness)
Skin plate	3 mm (thickness)

Table 2 Material strength of NMW test specimen

	Steel (SM490)		Concrete
	Yield strength (N/mm^2)	Tensile strength (N/mm^2)	Compressive strength (N/mm^2)
Experimental value	315	513	41.3

3.2.3 Test result

(1) Evaluations of load bearing performance and macroscopic rigidity

Figure 9 shows the relationship between the bending moment

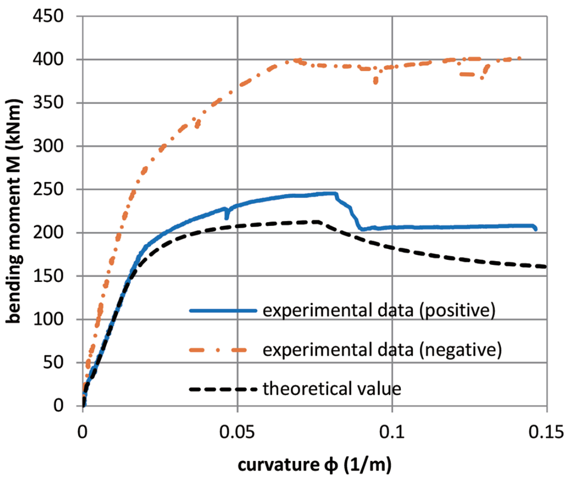


Fig. 9 M-φ relation of NMW bending test

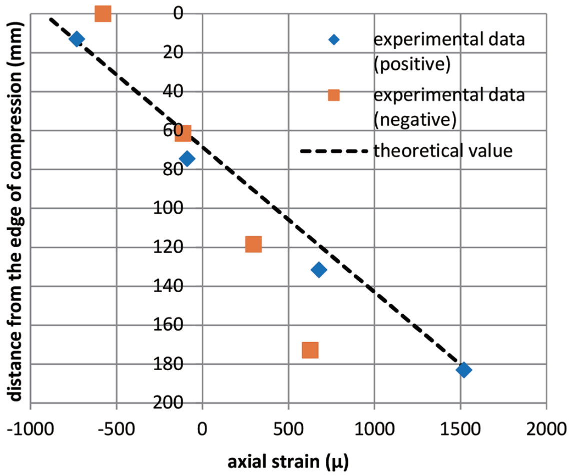


Fig. 10 Strain distribution of NMW bending test

generated at the center of the test piece calculated from the loading and the curvature at the same position calculated from the test piece strain. In the figure, together with the test values, the theoretical strength value calculated based on the main body structural model is shown. The maximum loading value obtained from the positive bending test exceeds by about 15% that of the result of the structural analysis, and even after the maximum loading value is exhibited, high resistance to deformation performance is exhibited. On the other hand, the maximum loading value obtained in the negative bending test exceeds by about 70% that of the result of the structural analysis. This can be attributed to the factor that the skin plate (situated at the outermost periphery on the tension side) that is not considered as a structural component member for the structural analysis is resisting across the entire width.

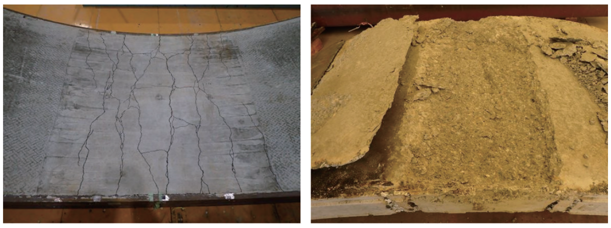
In addition, in the elasticity range on a design basis, the bending rigidity obtained from the positive bending test shows good agreement with that of the structural analysis. On the other hand, in the negative bending test, as aforementioned, since the skin plate resists as a structural component member, bending rigidity higher than that of theoretical values is exhibited.

(2) Evaluation of microscopic behavior of component member

Distribution in the girder height direction of the axial strain at the yielding load level is shown in **Fig. 10**. The straight line in the figure shows the theoretical values calculated from the main body structural model. The strain distribution in the positive bending test shows approximate agreement with that of the theoretical values, and thus the microscopic behavior can be evaluated by the main body structural model. In the negative bending test, likewise the evaluation of load bearing performance, due to the contribution of the skin plate, rigidity is enhanced, and therefore, the strain generated has become smaller than the theoretical values.

(3) Fracture mode evaluation

Photo 2 shows the states of the test piece on the inner space side and the ground side after the tests. In the positive bending test, sufficient crack dispersibility is secured on the inner space side. Furthermore, on the ground side, concrete collapse is observed as assumed. Although graphical presentation is omitted, in the negative bending test, a similar trend was observed.



(a) Inside (b) Outside

Photo 2 Ultimate state of NMW bending test

3.2.4 Summary of the evaluation of the main body performance

The major points of the load bearing performance of the main body of NMW™ confirmed in the single piece bending test are summarized below.

1) Evaluation of the load bearing performance on the conservative side is possible by means of using the main body structural model.
2) The microscopic behavior of the component member in the positive bending test can be evaluated with the main body structural model with high accuracy.
3) The fracture mode shows concrete collapse which agrees with the estimation by the main body structural model.
4) In the negative bending test, since the skin plate is not considered as a structural component member, both the loading bearing performance and the rigidity exceed the assumptions provided by the main body structural model.

Since all of the above four items have been confirmed, the NMW™ main body has been verified as a composite structure.

3.3 Longitudinal joint performance of NMW™

3.3.1 Test method

Two boxes each of the simulated segments were manufactured. These were connected with a dumbbell joint, and were used as a test piece, in which a four-point bending test was conducted. The outline of the test is shown in **Fig. 11**, and the outline of the test specimen is shown in **Fig. 12** and **Table 3**.

3.3.2 Structural model

The dumbbell joint is pin connected to the main girder of the segment, allowing freedom of rotation. This structure suppresses the

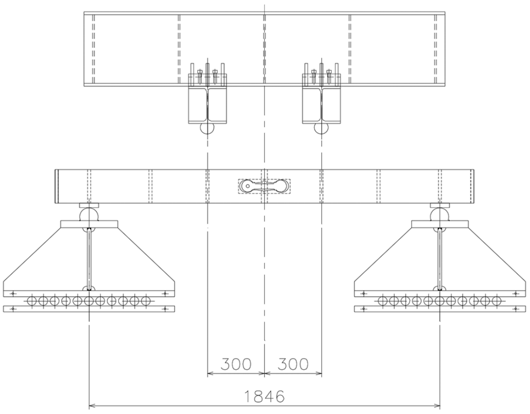


Fig. 11 Joint bending test of NMW

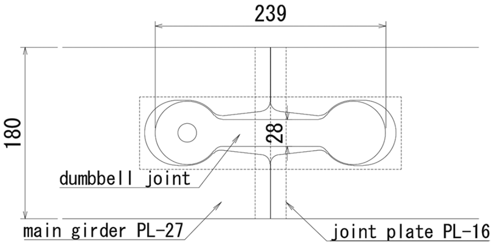


Fig. 12 Joint detail of NMW test specimen

Table 3 Specification of NMW joint test specimen

Width	239 mm
Height	28 mm (shaft center)
Thickness	27 mm (same to main girder)

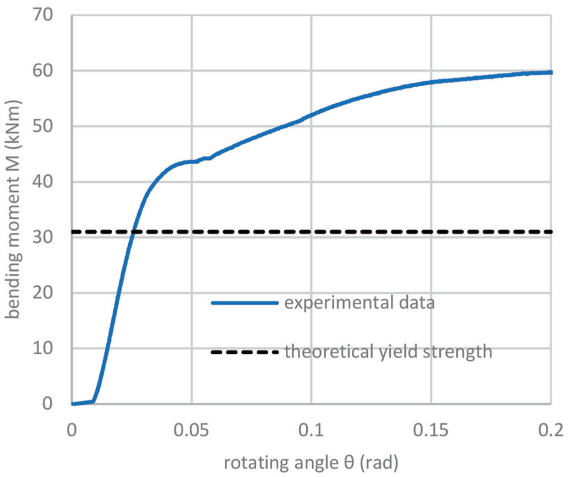


Fig. 13 M-θ relation of NMW joint bending test

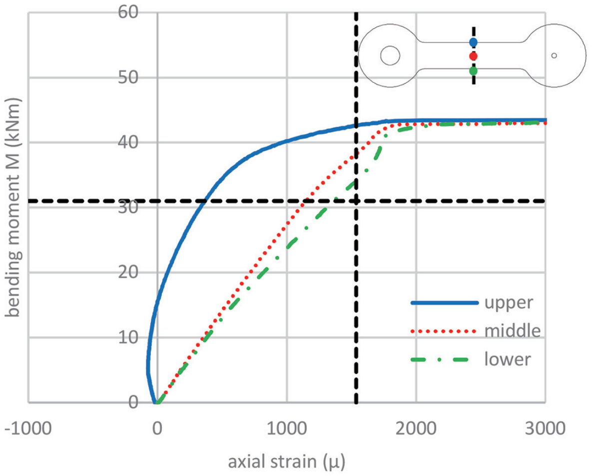


Fig. 14 Strain history of NMW joint bending test

influence of the secondary bending moment acting on the dumbbell shaft section so that the maximum shaft section load bearing performance can be exerted. As a result, in the structural analysis, the dumbbell shaft section is treated as a tension member like a conventional bolt, and a model that provides evaluation on the conservative side (hereafter referred to as the "joint structure model") is employed.

3.3.3 Test result

(1) Evaluation of load bearing performance

Figure 13 shows the relationship between the bending moment generated at the center of the test specimen calculated from the loading and the joint rotation angle calculated from the measured values of joint opening or closing. In the figure, together with the test values, the yielding bending moment obtained from the joint structure model is shown.

The test was terminated when the joint rotation angle reached 0.2 rad, the limit of the test machine capability. The maximum load at this point is about two times higher than the yielding bending moment. Furthermore, in the range below the yielding bending moment, linearity is maintained between the bending moment and the angle of rotation, which macroscopically shows elasticity behavior.

(2) Evaluation of microscopic behavior of component member

Figure 14 shows the strain history of the dumbbell joint shaft section with respect to the acting bending moment. Strain was measured at the three locations on the upper edge, the middle position, and the bottom edge at the center of the longitudinal direction of the dumbbell joint shaft. In the figure, together with the test results, the yielding bending moment and the yielding strain of the steel are shown. When the yielding bending moment is exerted on the joint, all of the strain generated in the shaft section is below the yielding strain of the steel, and it is considered that the microscopic behavior of the dumbbell joint is evaluated on the conservative side by the joint structure model. In addition, although the shaft strain grows larger in the order from upper edge, center, and lower edge, the entire section is basically in the tension range, and the free rotation of the dumbbell joint can alleviate its load. Furthermore, in the region above the yielding bending moment, strains at three locations become nearly equal, and the entire section assumes an equally tensional state.

(3) Fracture mode evaluation

Photo 3 shows the ultimate state of the NMW™ joint after the loading test. Although the shaft is elongated and deformed significantly, abnormalities like cracks are not recognized in the steel and/or in the welds, and the occurrence of brittle fracture and/or the escape of the joint are not recognized.

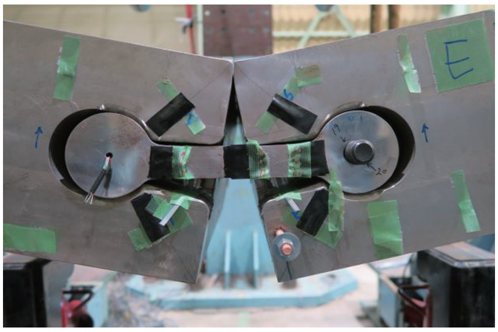


Photo 3 Ultimate state of NMW joint bending test

3.3.4 Summary of the evaluation of longitudinal joint of NMW™

Major items confirmed in the joint bending test conducted regarding the NMW™ longitudinal joint load bearing performance are summarized below.

1) With the joint structure model, load bearing performance is evaluated on the conservative side by using the joint structure model.
2) The component member microscopic behavior is evaluated on the conservative side by using the joint structure model.
3) Even in the ultimate state, the joint will not become brittle or come off.

4. Conclusion

In recent years, although the entire demand for the shield tunnels is on a gradual downward trend corresponding to the near completion of the development of the sewage system and/or the major subway railway network, it is anticipated that the needs for exploiting underground space will continue to be maintained at a certain level of scale such as for the development of a highway network in urban areas to solve traffic congestion, extension of subway railways, and the development and exploitation of underground rivers to counter devastating torrential rain falls. On the other hand, to secure safety in natural disasters beyond our suppositions, and to optimize the life cycle cost (LCC) targeting longer service life, needs for shield tunnels are growing increasingly sophisticated. Concentrating efforts around the lineup of composite segments with special fitting joints of the NMW™ and NM segment™, we are determined to promote further product development and proposal activity in the market more aggressively.

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