Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 78 (1998)

Artikel: Evaluation of steel-concrete composite structures applied for multi-micro shield tunnel

Autor: Tanaka, Yoshihiro / Mochizuki, Osamu / Hirono, Tuyoshi

DOI: https://doi.org/10.5169/seals-59039

Evaluation of Steel-concrete Composite Structures Applied for Multi-micro Shield Tunnel

Yoshihiro Tanaka
Research Manager
Taisei Corporation
Yokohama, Japan

Osamu Mochizuki
Construction Manager
Taisei Corporation
Yokohama, Japan

Tuyoshi Hirono
Design Manager
Taisei Corporation
Tokyo, Japan

Kouichi Kanou
Research Engineer
Taisei Corporation
Yokohama, Japan

Summary

Metropolitan Expressway Public Corporation is now developing the technically challenging multi-micro shield tunneling (MMST) method to construct huge span tunnels without use of the cut-and-cover method in urban areas minimizing environmental affects as well as the total construction cost. The experimental and analytical investigations of the flexural, shear and tensile resistant behaviors of the sandwich structure, the segment connector and the composite joint have been conducted to develop the reliable and cost effective joint structures as well as the design method for the MMST. A finite element approximation applying the concrete constitutive model based on fracture energy can well simulate the flexural and shear nonlinear behavior of the sandwich beam.

1. Introduction

It becomes difficult to construct the cut-and-cover tunnel for highway in urban areas because of the restrictions to obtain the private estate in the planned construction area, and to keep the traffic flow capacity as well as to control the environmental aspects. The MMST method is proposed for those demands to construct the huge span tunnel providing the multiple traffic lanes without disturbing the ground traffic flow. Underground air ventilation ducts equipped for the multi-lane expressway junction tunnels are now under construction by this method in advance of the huge multi-lane junction tunnels to confirm the construction process especially how to control well the shield machine with rectangular cross section and to verify the design method of the sandwich structure as well as the composite joint. Several technical developments have been and still being carried out for this project ; i.e., the development of both lateral and vertical sided shield machines, the cost effective reinforcement of the composite joint and the sandwich structure, and the design method for the composite structures including the structural checking for each construction stage. This paper is focused on the structural design verification for the underground air ventilation ducts being under construction as well as new proposals for cost effective composite joint and reinforcing the sandwich for future long span tunnel construction.

2. Construction Process of MMST

The general construction process illustrated in Fig. 2.1 are made up by the following stages ; 1) excavation shield tunnels and erection the segment alternatively using both lateral and vertical sided shield machines, 2) excavation inside the junction space among the shield tunnels and set up the joint reinforcement, 3) casting concrete into both shield tunnels made of steel segments and junction spaces reinforced by joint beams to build outer steel-concrete composite wall and slab for the final tunnel, 4) at a stretch excavation the inside of the final outer wall and slab without using any supporting members, 5) building the inner reinforced concrete walls and slabs for the traffic lanes. The structural requirements for the members are different for each construction stage and important to confirm the structural safety and to reduce the construction cost. There are three major structural requirements to solve as illustrated in Fig. 2.2. The first point is how to conduct the shear reinforcement for the sandwich structure as well as how to evaluate the shear and flexural behavior of the sandwich structure as an outer slab. The second requirement is how the segment connector can have better bending performance than the general steel segment at the shield tunnel construction stage as well as it can have better tensile performance than the general one as a sandwich slab at the construction stage of excavation the inside of the final outer slab. The last requirement is how the composite joint among the shield tunnels can conduct better shearing and bending performance than the general sandwich structure.

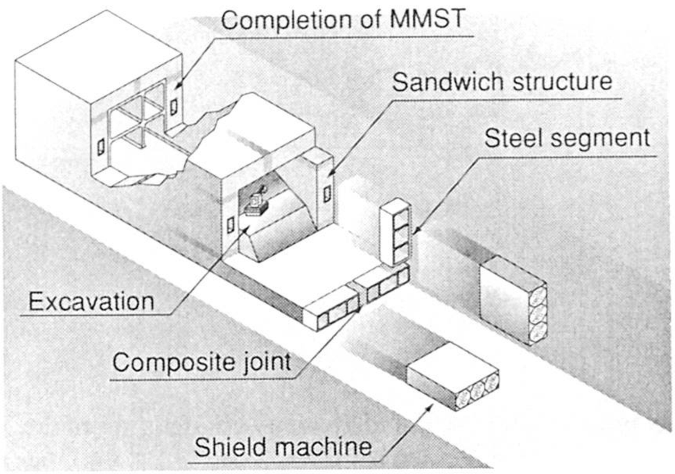

Fig. 2.1 Construction process of MMST

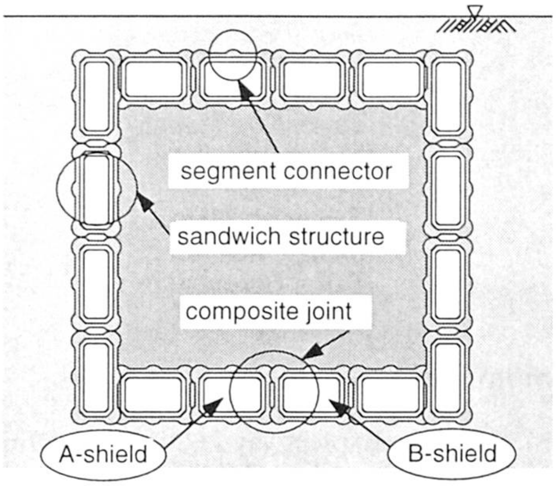

Fig. 2.2 Structural requirements for MMST

The dimensions of the steel segment frame for the underground air ventilation duct tunnel being under construction are 2.5m in height and 7.0m in width for the lateral sided shield machine as illustrated in Fig. 2.3. One ring of segment frame whose length is 1.2m, is composed of six pieces of segment and each segment is jointed by the segment connectors. The main segment frame is made of H-beam or channel-beam whose height is 30cm and it is covered with skin plate whose thickness is 6mm. It is also supported by four mid-columns per one segment ring. The shear connector set up perpendicular to the main frame is originally designed to transmit the reaction force caused by several jacks promoting the shield machine to the main frame without buckling. Both lateral and vertical sided shield machines manufactured for the construction of the underground air ventilation duct is illustrated in Photo. 2.1. Four corner circles equipped in the shield machine are designed to make up reinforced soil roofs around the main frame corners.

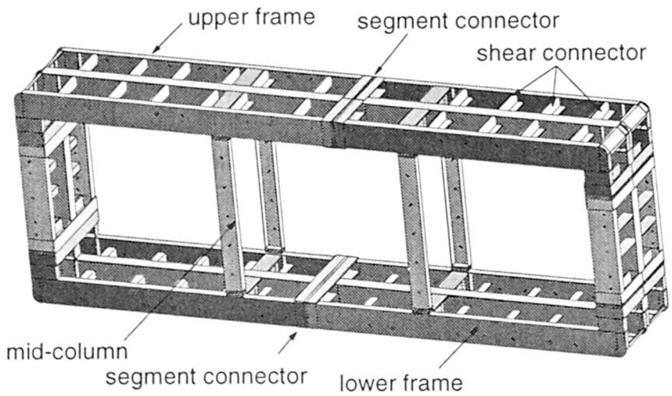

Fig. 2.3 A ring of steel segment frame

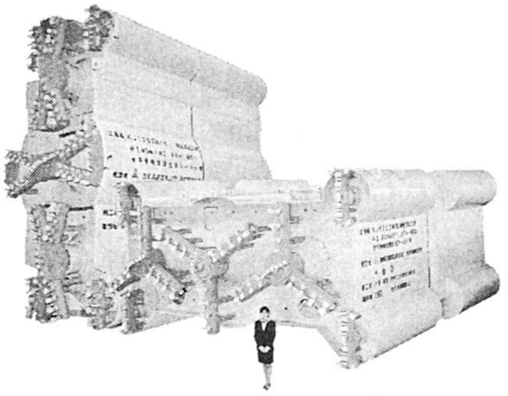

Photo. 2.1 Shield machines for MMST

3. Structural Concept and Experimental Program

3.1 Sandwich Structure

After casting concrete into the shield tunnel, the shield tunnel itself turns to be the sandwich structure. Two major questions come out in the process of the structural design for this structure ; 1) the shear connectors which are originally set for the reinforcement of the jacking system in shield machine, are good enough to transfer the shearing force, 2) the mid-columns as shown in Fig. 2.3 which are originally employed as supporting members, work sufficiently well for shear reinforcement. Three flexural and shear loading tests as shown in Fig. 3.1 have been carried out using 1/2 scale specimens. Case-1 is just same as the segment frame as shown in Fig. 2.3. The interval of four mid-columns is approximately same as the sandwich beam depth, therefore the diagonal abrupt cracks may be easily caused by the shear force. In addition, the mid-column is fixed to the upper and lower frames by high tension bolts which have smaller yielding capacity than the mid-column, so the shear reinforcement ratio is only 0.074%. Case-2 is reinforced for shearing force by fixing the deformed bars to the shear connectors as illustrated in Fig. 3.1. Hence the pitch of shear reinforcement reduces to about 22cm and the shear reinforcement ratio due to rebar becomes 0.153%. Case-3 is planned to evaluate the reinforcing effect by rebars on the shear capacity through the shear loading test. The concrete compressive strength are designed to be 24Mpa and the maximum aggregate size is to be 10mm considering size effect.

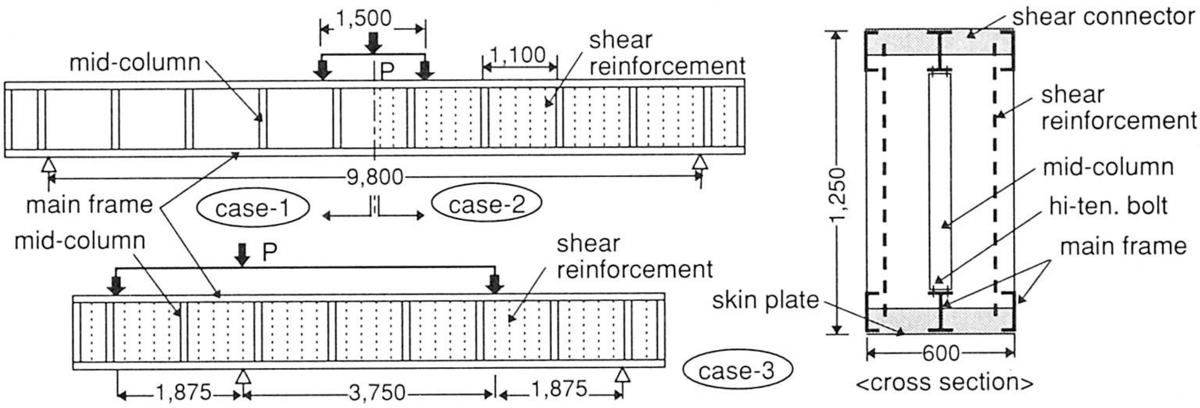

Fig. 3.1 Flexural and shearing tests arrangement for sandwich structure

3.2 Segment Connector

The segment connector used for the usual shield tunnel is designed to resist only for the bending moment due to the hydrostatic and earth pressure and it is required to tightly fit together each segment to prevent from leaking, while the segment connector for MMST is further required to resist for the tensile force as reinforcement of the final tunnel's outer wall . Therefore it is important from the design point of view how to separate the stress in joint bolts due to the first stage bending moment from the stress in these due to the second one. Flexural and tensile loading tests have been conducted for three specimens of segment connector as illustrated in Fig. 3.2. Case-A whose scale is 1/1, is the simplest connector to assemble quickly the segments each other and it is planned to investigate the tensile behavior of the lower joint bolts for the first stage bending moment as well as the three dimensional zig-zag effects on the bending resistance. Case-B whose scale is also 1/1, is an advanced connector modified from case-A. It is known from the analyses that case-A can not sustain the comparable tensile force to the main frame, because the end plates facing each other might deform easily by tensile force and it results in that the tension in

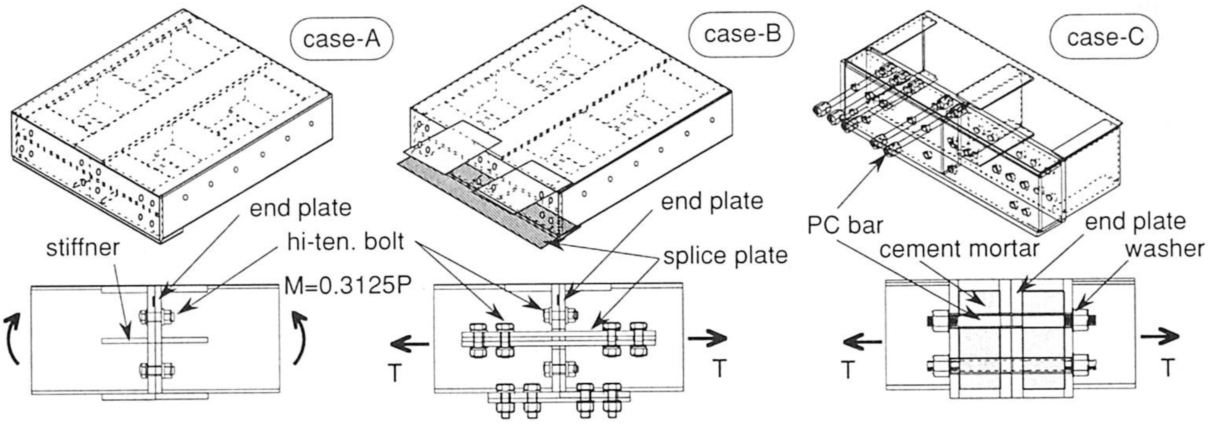

Fig. 3.2 Flexural and tensile tests arrangement for segment connector

each joint bolt does not distribute with even shares. The design concept of case-B is that the facing short bolts work only for the first stage moment while the splice plates resist only for the second stage moment. The specimen case-C whose scale is 1/2, is a further advanced connector combined from both case-A and case-B. Case-B needs to tie a lot of hi-tension bolts with the splice plate under controlling torque, hence this would take a long cycle time to assemble the segments. Case-C is composed of the steel plate box instead of the end plate and PC long joint bars. Shrinkage compensating cement mortar is injected in advance into the steel plate box because it might increase the rigidity which must smoothly transfer the tensile reaction force in joint bars to the main frame. It is noted that the lower PC long joint bars work for the first stage bending moment while the upper PC long joint bars sustain for the second one.

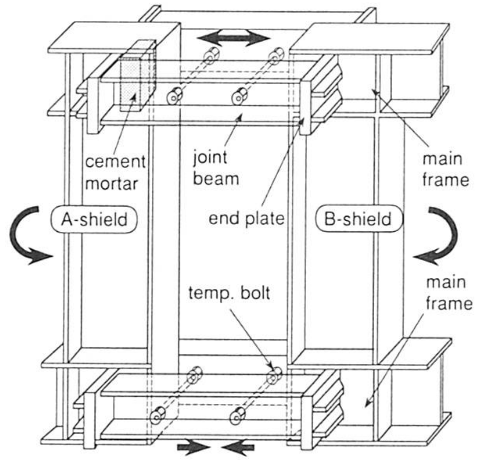

Fig. 3.3 Concept sketch of composite joint

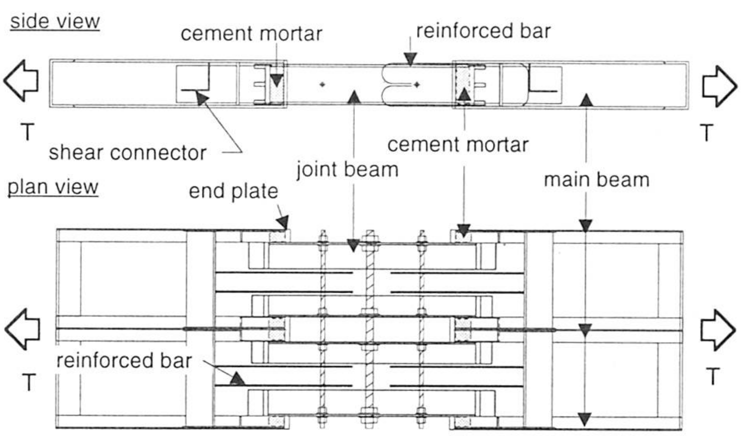

Fig. 3.4 Tensile test arrangement of composite joint

3.3 Composite Joint among Shield Tunnels

The joint structure assembled inside the junction space among the shield tunnels, need satisfy at least two requirement ; 1) it should keep the comparable flexural and shear resistance compared with the sandwich structure, 2) it needs to be adjustable for the dislocation of the segment frame due to the construction error without reduction of structural performance. A typical joint method may be to set the longitudinal joint rebars and stirrups to transmit the tensile force due to bending moment in main frame via bond stress on joint rebars and shear stress in concrete. This type of joint however, can not usually possess the full flexural capacity same as the sandwich structure because of the limitation of joint rebar's location and space. The concept sketch of proposed composite joint is illustrated in Fig. 3.3. The structural concept for this joint is that 1) joint beams located in the center of the main frame are employed to directly transmit the tension to the main frame, 2) the cement mortar injected into the spaces which are located in both ends of joint beam, acts to transmit the tension from the main frame to the joint beam via compressive stress and it can adjust the dislocation of the segment frame. In advance of the flexural and shear loading test of this composite joint, the fundamental tensile loading test for the assembled joint member has been carried out to confirm force transmission mechanism and tensile capacity. The test arrangement for one ring segment frame scaling 1/2, is shown in Fig. 3.4. Concrete is cast inside the joint space to consider the lateral confinement effect of concrete on the lateral deformation of joint beams.

4. Experimental Results and Evaluation

4.1 Flexural and Shear Behavior of Sandwich Structure

The comparisons of the experimental results and the numerical analyses for the sandwich structure are demonstrated in Fig. 4.1. The crack pattern of case-1 to -3 are compared with the principle strain distribution calculated by the FE analysis in Fig. 4.2. The load and deflection curves for case-1 and -2 seem to be similar each other, but the failure modes are different ; case-1 indicates shear failure while case-2 shows flexural failure. The failure modes difference is demonstrated in the crack pattern ; 1) crack-A and B were open just before the final load but diagonal crack-C

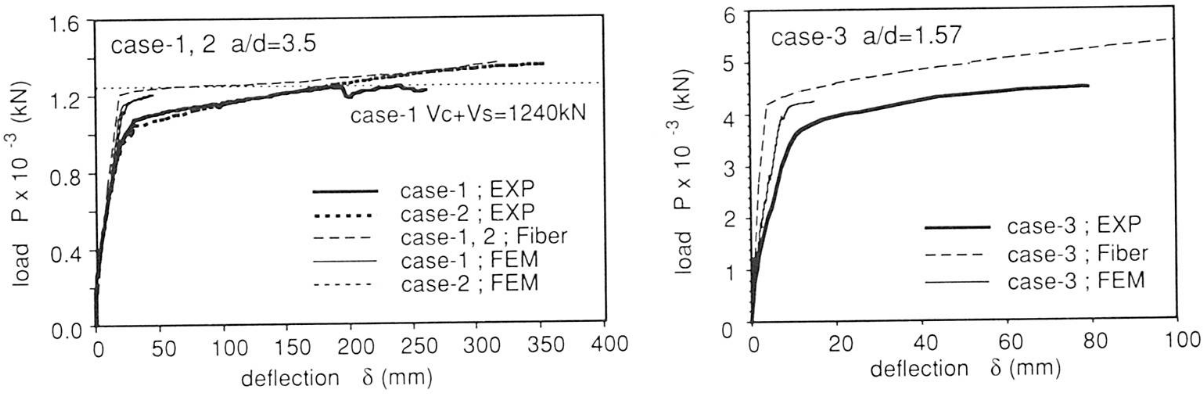

Fig. 4.1 Load and deflection of sandwich structure

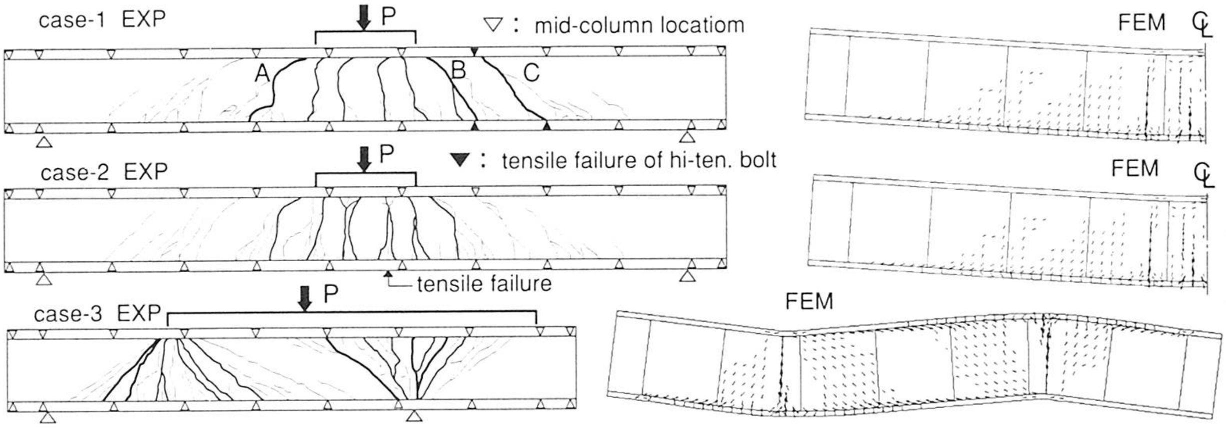

Fig. 4.2 Crack pattern of tests and FE analyses

which does not cross the mid-column, opened abruptly at the final load where the hi-tension bolts both ends of mid-column were failed, 2) crack pattern of case-2 is scattered wider than case-1 and the typical flexural cracks increased uniformly in width to result in the tensile failure in the main frame at the final load. These difference can be also explained by simple hand calculation ; 1) the flexural capacity by RC formula is P_{flx}=1100kN, 2) the shear capacity by Okamura's formula results in P_{s1}=1220kN for case-1 and P_{s2}=2170kN for case-2, respectively. Case-3 indicates shear failure mode and its crack pattern demonstrates scattering uniformly compared with case-2 because of difference of shear-bending ratio. It is observed in all cases that all cracks begin to grow from the shear connectors in the main frame. The capacity predictions for case-2 and 3 by the FE model demonstrate good agreement, but estimation for case-1 by the FE model does not result in the shear failure. The FE model can not estimate the proper deflection; the reason may be that the model does not include the confinement effect due to skin plate. The crack pattern results demonstrate nice agreement with test results. The capacity and deflection prediction for case-2 by fiber model agrees well with test results; this means RC theory can follow the flexural behavior of the sandwich structure.

4.2 Flexural and Tensile Behavior of Segment Connector

The load and deformation results are illustrated in Fig. 4.3. Most deflection in case-A after yielding is caused by the deformation of the end plate and the lower tension bolts. Segment connector case-A lost the bending resistance at the final load 3140kN by fracturing one lower bolt located near the main frame. This observation can be simulated even by the linear FE model. The web splice plate in segment connector case-B indicates yield at around the tension force 1200kN under which the elasto-plastic FE model can simulate accurately. The reason why the FE model underestimates the tension force for over the rage of yield point is that modeling of splice plate does not include the reduction of frictional force due to web's yielding. The final failure mode of case-B was a slip of the splice plate. It should be noted that all tension joint bolts for case-B and the lower PC joint bars for case-C were not set in the loading tests to separate a prior stress in bolts. The elongation of case-C indicates smaller than case-B and its yield point is not so clear because the end plate box injected cement mortar is so rigid that the stress from PC joint bar can spread over the main frame. The elasto-plastic FE model can predict quite accurately the final resistant capacity which was determined in test by the abrupt failure of all of the PC joint bars. In addition this model might predict precisely the elongation if the deformation of washer for the PC joint bars were considered into the modeling.

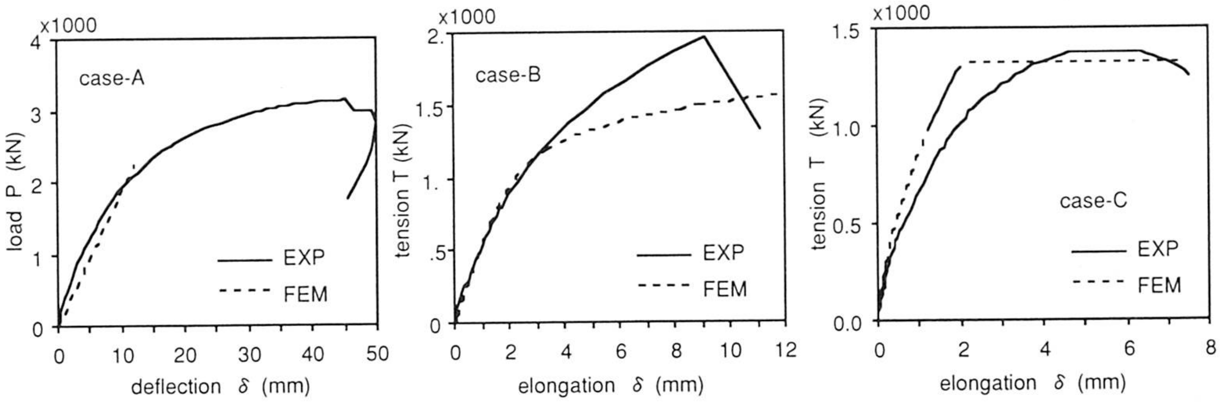

Fig. 4.3 Load and deformation of segment connector

4.3 Tensile Behavior of Composite Joint

The comparison of the test results and the FE model for the composite joint are illustrated in Fig. 4.4 and the deformation sketch by elasto-plastic FE model at yielding point is also illustrated. The first slope of rigidity at around 300kN in the test result comes from 'tension stiffness' caused by surrounding concrete. The yielding point at around 1100kN is mainly caused by yielding at the web plate of which thickness becomes normal in the main frame as illustrated in the deformation sketch. The yielding load predicted by the FE model is higher than the test result but the final load agrees quite well with the experiment. It should be noted that proposed composite joint can sustain the tensile capacity of the main frame without a serious damage in joint part.

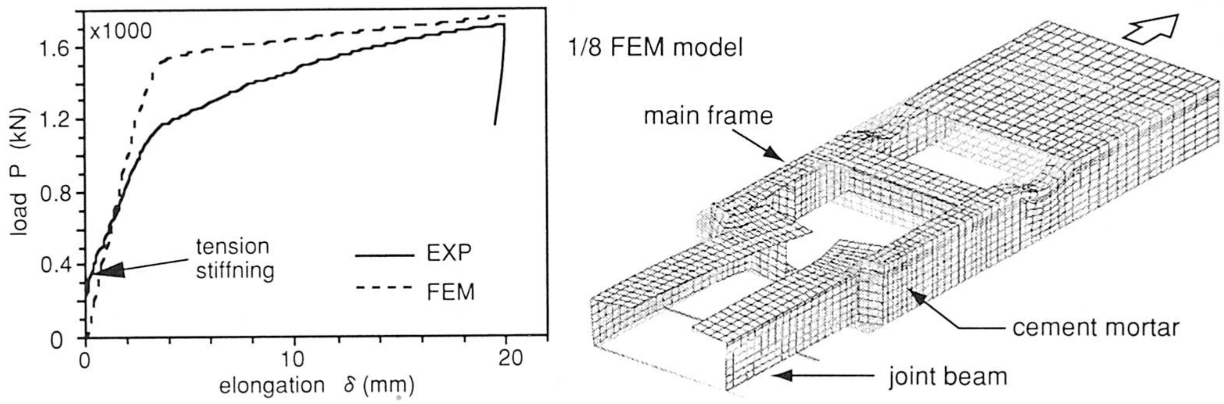

Fig. 4.4 Load and elongation of composite joint

5. Concluding Remarks

1) The sandwich structure for MMST is a multi-purposed useful structure for a huge span of tunnel and its flexural performance is similar to the reinforced concrete. 2) The mid-columns employed as supporting members are not good enough to keep the shear resistance hence the shear reinforcement by rebars with small pitch is useful for scattering the cracks and cost effective. 3) The design of the segment connector for MMST needs to be taken a careful consideration because of dual purposed usage. The segment connector of long PC bars with the cement mortar injected plate box indicates good performance for those requirement. 4) So far the tensile test result of proposed composite joint, the sandwich structure applying this composite joint must demonstrate good flexural and shear performance and also cost effective performance.