NONLINEAR ANALYSIS OF MECHANICAL JOINTS FOR MIXED STRUCTURES

Osama A**. KAMAL** and Osama O. **EL-MAHDY**[1]

ABSTRACT

Mixed steel-concrete structures are very interesting and attractive to bridge engineers, who are eager to promote technological innovation. In cable stayed bridges, the ratio of the side spans to center span becomes extremely small, and this causes negative reaction at the side spans. To alleviate this problem, mixed structures composed of steel girders for center span to minimize its dead loads and reinforced or prestressed concrete girders for side spans as counterweights have been recently proposed. Further, the idea had been successfully implemented for Normandie bridge in France and Tatara bridge in Japan.

The purpose of this work is to provide a general nonlinear finite element model to analyze the mechanical joints for mixed structural systems. Two-dimensional plane stress elements having two degrees of freedom at each node are used to idealize both steel and concrete components. Line interface elements having both normal and shear stiffnesses are placed at the interface between steel and concrete elements. The steel elements are modeled using an elastic-perfectly plastic model with a Von Mises yield criterion. The concrete behavior under compression is modeled using an elasto-plastic model with a Drucker-Pager yield criterion and associated flow rate. The concrete in tension is modeled using a smeared cracking model with tension cut-off, tension softening and variable shear retention. Analytical models for three mechanical joints are investigated in this paper. The analytical results are compared with the experimental ones. The comparison shows that the proposed model is accurate enough to predict the behavior of the mechanical joints. Finally, a new mechanical joint for mixed structures is proposed.

KEYWORDS: Mixed Structures; Mechanical Joints; Stud Shear Connectors; Experiments; Nonlinear Analysis; Modeling.

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INTRODUCTION

Structures that use steel and concrete combined together are generally called steel-concrete hybrid structures. The concept is very rational since it aims to utilize characteristics of each material appropriately in order to obtain higher performance as a result. This concept was implemented in the form of composite girder bridges in the middle of 20th century. In such structures, different materials are used to resist external forces almost equally at any section along its length. They are called "Composite Structures". On the other hand, long span cable-stayed bridges, which use steel girders for center spans to minimize its dead load and prestressed concrete girders for side spans as counterweights, have been recently constructed. Such structures in which different materials are used for different parts are called "Mixed Structures" (see Fig.1). This new type of cable-stayed bridges has recently attracted attention since it allows for longer and larger bridges. Normandie bridge in France (Virlogeus 1993), the innovative designed bridges by Calatrava in Spain, Ikuchi bridge, Tatara bridge, and the world's longest cable-stayed bridge of the Honshu-Shikoku Bridge Project in Japan (Ikeda 1991 and Echigo 1994), are examples of such bridges.

The mechanical joint between steel and concrete members plays the most important role in the creative design and practical application of these mixed structures, since it requires a sufficient capability in transfer of all internal forces. Research related to the joint of mixed structures is little, whereas the practical applications have been implemented extensively in several countries. A series of static experimental works for three types of mechanical joints were conducted by Hino et al. (Hino 1984 and Hino 1985) and Tajima et al. (Tajima 1982) to obtain the basic data with respect to finding a rational method for predicting the behavior of the connections of mixed steel-concrete beams.

The main objectives of this paper are :(1) to describe a simplified and efficient nonlinear finite element analytical model for the mechanical joints which were successfully implemented in mixed structures; (2) to demonstrate the applicability of the proposed model by comparing the predicted analytical behavior with the behavior observed in the laboratory; and (3) to discuss the effects of various material parameters and their relation to various failure modes. To this end, the rest of this paper is organized as follows. First, different types of mechanical joints are presented followed by the nonlinear finite element model. Next, the numerical technique is outlined. Then, the analytical results are presented and discussed. Finally, the conclusions are drawn for this work.

MECHANICAL JOINTS APPLIED TO MIXED STRUCTURES

The optimum and practical jointing methods for mixed steel-concrete structures are the application of the stud shear connectors which have been widely used in ordinary composite girders, the application of the high tensile bolts used for steel structures, and their combinations. Therefore, this type of studs is adopted in the mechanical joints discussed hereafter.

Figure 2 shows the details of three mechanical joints investigated by Hino et al. Flexural resistance of each joint is retained by means of prestressing or anchoring the tensile reinforcing bars to the steel beam, in addition to the reinforcement in the joint represented by hoop anchor bars, shear connectors, and high-strength bolts. Joint-R consists of a steel channel section with three hoop anchor bars of 13 mm diameter. Joint-S installs six studs on the upper and lower flanges of the channel section. The studs are 13 mm in diameter and 75 mm in height. Concrete of joint-B is connected tightly to the channel with two high-strength bolts, of which yield point is 1100 MPa (11220 Kgf/cm^2) and diameter is 10 mm.

Joint-S has been successfully used in many bridges such as Dusseldorf-Flehe bridge in Germany and other bridges, while the types of joint-B have been widely used as the connections of segmental structures. A series of static tests of joints-R, -S, and -B were carried out to obtain basic data with respect to a rational method for connecting mixed structures. All tested beams consist of an H-shape steel beam and either prestressed or reinforced concrete beam. The beams were simply supported and of 2000 mm span. The experimental results showed that, for joints-B and -S, the slip on the steel-concrete interface is increased gradually with the increase of applied external load, which resulted in significant reduction of the flexural rigidity. Whereas, joint-R retained a sufficient stiffness up to almost the failure load. Furthermore, little cracks were produced in the concrete region of joint-R before failure. The failure occurred due to crushing of concrete outside the joint region. However, for joints-B and -S, cracks were initiated at small loads and the tested beams were failed due to crushing of concrete at the joint. More details about the experimental results may be found in Hino et al. (Hino1984 and Hino1985).

NONLINEAR FINITE ELEMENT MODELING

The finite element method, because of its ability to take into account the conditions of equilibrium, compatibility, and nonlinear material behavior, is a valuable analytical tool which can be used to : (1) directly predict the structural response in the entire load range up to failure; (2) gain greater understanding of the behavior so that simpler but realistic models can be developed; and, (3) study the effects of important parameters on structure behavior; thus providing a firmer basis for code provisions.

This section presents the finite element modeling of the previously tested mechanical joints. Two-dimensional isoparametric quadrilateral plane stress elements having two degrees of freedom at each node are used to idealize both concrete and steel members (see Fig. 3). The reinforcement bars can be included either in a smeared form as a part of the concrete element, or as a discrete bar element passing through the quadrilateral element. Line interface elements having both normal and shear stiffnesses are arranged at the interface between steel and concrete parts and around the stud connectors. These interface elements have no physical dimensions and thus they are used to connect two separate nodes occupying the same physical position (see Fig. 3). The initial dimensions of the interface elements are specified as zeros in which case the contact is initially full (i.e., the concrete and steel members are initially in contact with each other). Details of finite element idealization of Joint-S are shown in Fig. 4.

The tested mixed beam specimens consist of two components: steel and concrete. In order to obtain adequate accuracy in the analysis of these specimens, realistic constitutive relations for the materials should be used in the calculations. Consequently, material nonlinearity must be employed in the present analysis. These subsections are devoted to describe the nonlinear material modeling of the tested mechanical joints. More details about the used models are well documented in ASCE (ASCE1982) and Chen (Chen1982). The analysis was carried out on a SUN SPARC IPX workstation using the finite-element-program DIANA, version 5.1. The material coded as a user-defined subroutine to the program.

Concrete Elements

In tension, the concrete material is idealized as a linearly elastic material with the inclusion of a descending branch in the stress-strain curve as shown in Fig. 5. A smeared cracking model was utilized, in which any cracking is assumed to be embedded, smeared over the tributary area (volume) of the an entire integration point (De Borst 1987). Cracking has occurred when the principal tensile stress exceeds the concrete tensile strength. Bearing in mind that cracks may be closed and re-opened again, a cracked element is checked in every iteration step for closure and re-opening: a crack is closed or opened up if the stress normal to the crack is compressive or tensile, respectively. Material properties at a given point are changing as progressive failure takes place. Before cracking, the material is assumed to be isotropic. Whereas, after cracking and due to presence of the crack surface, the material become anisotropic. For cracked element, the modulus of elasticity "E" is reduced to zero perpendicular to the principal tensile direction (Gerstle 1981).

Furthermore, parallel to the crack surface, the shear modulus "G" with a reduction factor "β" is re-inserted in the element constitutive matrix. The use of a shear modulus, "βG" with (0.0<β≤1.0) does not only remove most of the numerical difficulties, but also improves the realism of the cracking phenomena generated during the finite element analysis. For instance, the shear modulus "βG" represents the aggregate interlock that occurs across an opened crack (Gambarova 1987 and Balakrishnan 1987).

The constitutive anisotropic tangent stiffness matrix for cracked concrete plane stress state is defined as follows:

$$\begin{Bmatrix} d\sigma_1 \\ d\sigma_2 \\ d\tau_{12} \end{Bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & E_c & 0 \\ 0 & 0 & \beta G \end{bmatrix} \begin{Bmatrix} d\varepsilon_1 \\ d\varepsilon_2 \\ d\gamma_{12} \end{Bmatrix} \quad \text{(1)}$$

in which E_c is the tangent stiffness of concrete, the 1-direction is perpendicular to the crack and the 2-direction is parallel to the crack.

Furthermore, since the intact concrete between cracks is still capable of transferring some tensile stress, a descending branch for the tensile stress-strain curve of concrete is utilized in the present analysis. The use of this descending branch is often referred to as tension stiffening or tension softening. Equation (2) gives the tension softening model which is used in the present analysis (Reinhard et al. 1986).

$$\frac{\sigma_{nn}^{cr}}{f_t} = \left[1 + \left(3\frac{\varepsilon_{nn}^{cr}}{\varepsilon_u}\right)^3\right] \exp\left(-6.93\frac{\varepsilon_{nn}^{cr}}{\varepsilon_u}\right) - 0.027\frac{\varepsilon_{nn}^{cr}}{\varepsilon_u} \quad \text{(2)}$$

where f_t is the concrete tensile strength, σ_{nn}^{cr} is the tensile strength normal to the crack, ε_{nn}^{cr} is the tensile strain normal to the crack, and ε_u is the ultimate tensile strain.

In compression, as shown in Fig. 5, the concrete is modeled by an elasto-palstic model with a Drucker-Prager yield criterion (i.e. failure will occur for all states of stresses for which the largest of Mohr's circles is just tangent to the envelope). Once the concrete fails in compression, it can never regain any strength. Furthermore, the Poisson's ratio remains constant at any strain level. For concrete, the cohesion can be calculated from Eq. 3 (DIANA 1993) as follows:

$$C = f_c^{'} \frac{1-\sin\varphi}{2\cos\varphi} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3)}$$

where $f_c^{'}$ is the compressive strength of concrete and ϕ is the angle of friction. Moreover, for simplicity, the dilatancy angle is taken to be equal to the friction angle (i.e. associated plasticity).

Steel Elements

The steel members and reinforcing steel bars are idealized as an elastic-perfectly plastic model with a Von Mises yield criterion (i.e. yielding begins when the octahedral shearing stress reaches a critical value k). The idealized stress-strain curve for steel member used in the present analysis is shown in Fig. 6.

The prestressing steel exhibits considerably higher strength than reinforcing steel. It has a greater elastic range, no distinct yield plateau, and a distinct but relatively short strain hardening region. In the present analysis, the closely matching experimental stress-strain curve of prestressing steel is used (see Fig. 7).

NUMERICAL TECHNIQUE

An incremental-iterative technique (i.e. Modified Newton-Raphson Method) is utilized in the present analysis. In this technique, the load is applied incrementally, but after each increment successive iterations are performed. In general, convergence of a solution is attained before going on to the next load increment. Before each new load step, the tangential stiffness matrix is updated.

The nonlinear analysis is carried out using either energy or force controlled convergence criterion. The obtained results are almost the same for both energy and force controlled, however the running time for force controlled analysis was about 60% of that for energy controlled analysis (i.e. the convergence is faster by the force controlled analysis).

ANALYTICAL RESULTS AND DISCUSSION

A preliminary linear analysis with an applied load equal to 140 KN was carried out in order to estimate the maximum stresses and to scale the first load-step for the nonlinear analysis. It should be mentioned that, the effect of self-weight of the specimen was neglected in the analysis. From the obtained results, it can be concluded that if the applied load is multiplied by 0.25, the tensile stress of the marked elements will just to be cracked (see Fig. 4).

Consequently, in the nonlinear analysis, a first two load steps each of 17.5 KN are carried out for which the structure should still be completely linear, followed by fifteen load steps each of 7 KN until a total load of 140 KN is attained. For further load steps, the analysis results do not show any noticeable improvement, since the concrete has completely collapsed due to cracking and crushing.

In the analytical model, the material properties were assumed as follows:

A. Concrete

Compressive strength	= 63 MPa
Tensile strength	= 3.7 MPa
Modulus of elasticity	= 20 GPa
Poisson's ratio	= 0.20

B. Steel

Steel section

Yield stress	= 235 MPa
Modulus of elasticity	= 210 GPa
Poisson's ratio	= 0.30

Reinforcing bars

Yield stress	= 295 MPa
Modulus of elasticity	= 210 GPa

Prestressing bars

Yield stress	= 1080 MPa
Ultimate stress	= 1225 MPa
Modulus of elasticity	= 210 MPa

Moreover, the shear stiffness for all interface elements around the channel section and studs was assumed to be zero value. On the other hand, in order to simulate the bearing resistance of the concrete to the deformations of channel section and studs, the normal stiffness for the hatched interface elements was changed from 1.0×10^8 to 1.4×10^8 KN/m^3. The normal stiffness for all other interface element was assigned a zero value.

In order to verify the applicability and accuracy of the proposed model, the cracking moment, ultimate moment, and the load-deflection relationships were obtained and compared with the experimental results conducted by Hino et al.

Cracking and Ultimate Moments

Generally, for the three mechanical joints, the initial cracks were started from the bottom surface at a section adjacent to the joint and then propagated diagonally into the joint region. The failure occurred due to crushing of concrete at the outside of the joint region. The experimental and analytical cracking and ultimate moments are given in Table 1. For joints-S and -B, the calculated values agree well with the experimental ones. However, for Joint-R, the analytical values were 18% less than the experimental moments.

Table (1) Cracking and Ultimate Moments

Joint Type	Cracking Moment (KN.m)			Ultimate Moment (KN.m)		
	Experimental	Analytical	$\frac{Mcr^*}{Mcr}$	Experimental	Analytical	$\frac{Mu^*}{Mu}$
	Mcr	Mcr*		Mu	Mu*	
Joint-R	20.6	16.7	0.81	54.8	44.9	0.82
Joint-S	15.6	14.9	0.96	47.0	46.1	0.98
Joint-B	20.6	19.6	0.95	49.4	46.4	0.94

Load-Deflection Relationships

Figure 8 shows the experimental and analytical load-deflection curves at the mid-span for joints-R, -S, and -B. In general, the slip occurred at the contact surface of steel-concrete beams resulted in significant reduction of the flexural rigidity of mixed beams, especially under loads greater than the decompression load. From this figure, it can be concluded that the measured deflection values agree well with those calculated using the proposed model.

Proposed New Mechanical Joint

Based on the available experimental results, a new mechanical joint which can be applied to mixed steel-concrete structures is proposed. Figure 9 shows the details of the proposed joint. In this joint, stud shear connectors are welded to the upper and lower flanges of the steel member. The size and number of the studs are determined so that the ultimate moment of the joint is equal to that for concrete member. Furthermore, the ultimate load of the stud which is applied at one third point from the stud base can be calculated using the following formula (Fisher et al. 1971):

$$Q_u = 15812 A_S \sqrt{f_C' \, E_C} \quad \text{.................................... (4)}$$

where

Q_u = design shear strength at ultimate limit state (KN)
A_s = cross-sectional area of the stud (m^2)
f_c' = characteristic cylinder strength of concrete (MPa)
E_c = modulus of elasticity of concrete (GPa)

At the end of the steel member, two end plates are welded at both sides of the joint, also two plates are fixed using high-strength bolts. These plates confine the concrete at the joint; thus preventing it from expanding transversely. The reinforcing bars or prestressing cables are anchored to the end plates. The thickness of the end plates is determined assuming that it is simply supported at the four sides and carries a prestressing force which is distributed to the area of the anchor plate. In placing concrete, the end plates are used as a part of the form and special care should be taken so that the stress concentration does not occur at the interface between steel and concrete members.

CONCLUSIONS

This work presents a general nonlinear finite element model for analysis of mechanical joints for mixed structural systems. In the finite element model, two-dimensional isoparametric quadrilateral plane stress elements having two degrees of freedom at each node are used to idealize both steel and concrete members. Line interface elements having both normal and shear stiffnesses are placed at the interface between steel and concrete elements. The steel elements are modeled by an elastic-perfectly plastic model with a Von-Mises yield criterion. The concrete behavior under compression is modeled by an elasto-plastic model with a Druker-Prasger yield criterion and associated flow rate. On the other hand, the concrete in tension is modeled using a smeared cracking model with tension cut-off, tension stiffening, and variable shear retention.

Three types of mechanical joints are considered. For each joint, the load-deflection curve and cracking pattern are obtained using the proposed analytical model. The obtained analytical results compared well with the experimental ones. The comparison indicates that the proposed model is accurate enough to predict load-deflection, cracking, and ultimate moments of the mechanical joints. The proposed analytical model can be used for different types of mechanical joints. This makes it is possible to reduce the high costs of experimental works. Also, a new mechanical joint for mixed steel-concrete structures is proposed.

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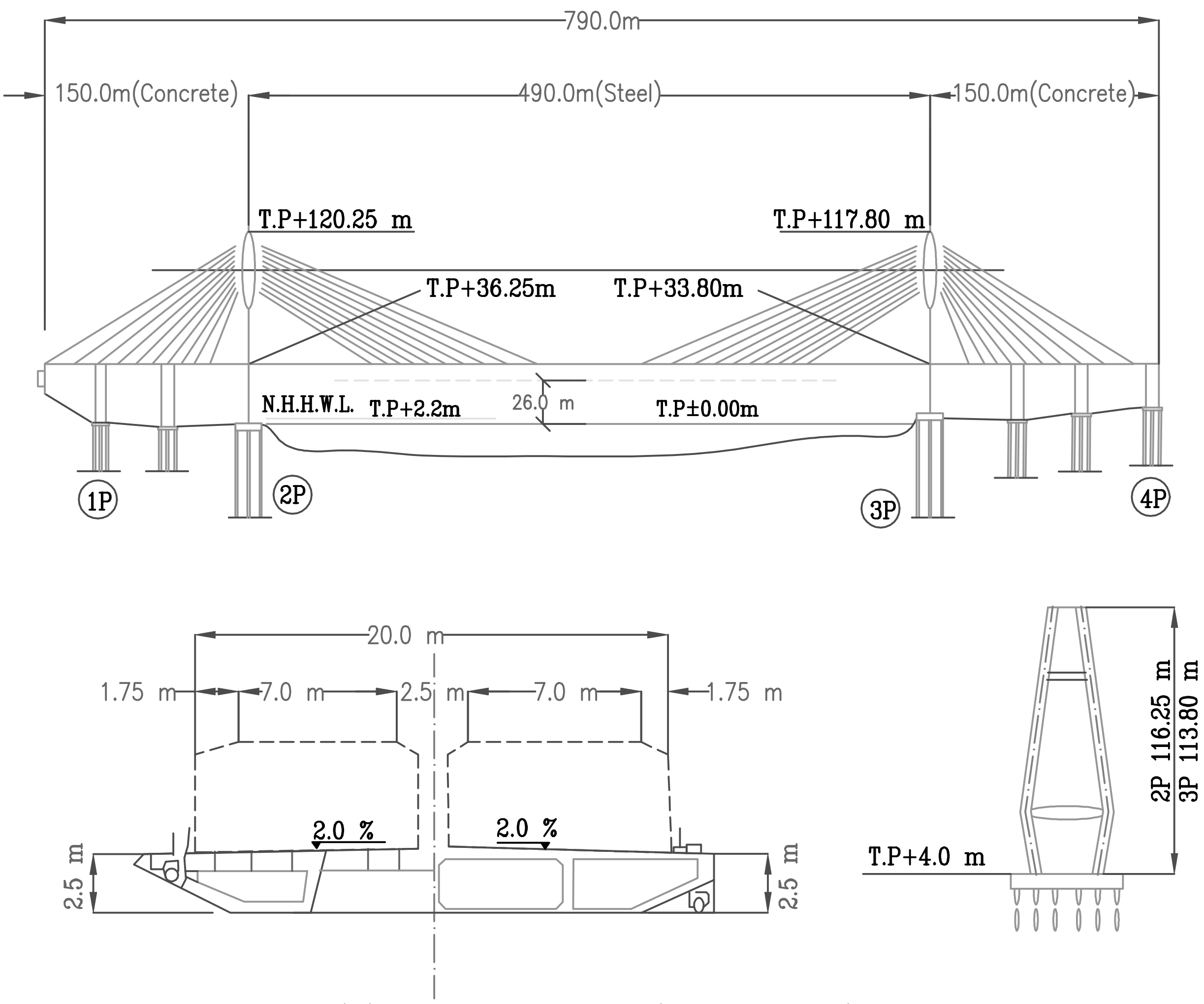
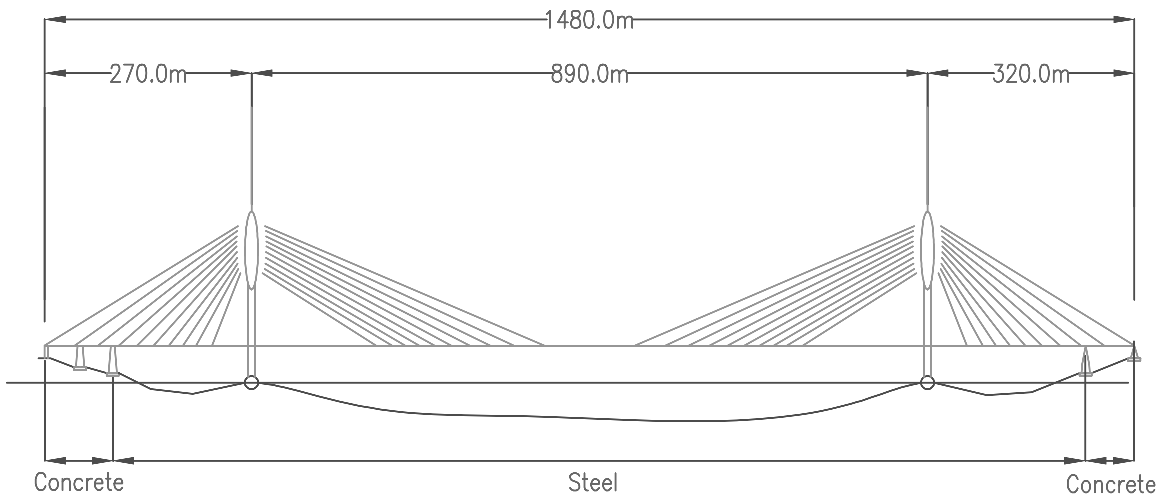


(a) Ikuchi Bridge (Ikeda 1991)



(b) Tatara Bridge (Echigo et al. 1994)

Fig. (1) Steel–Concrete Mixed Structures

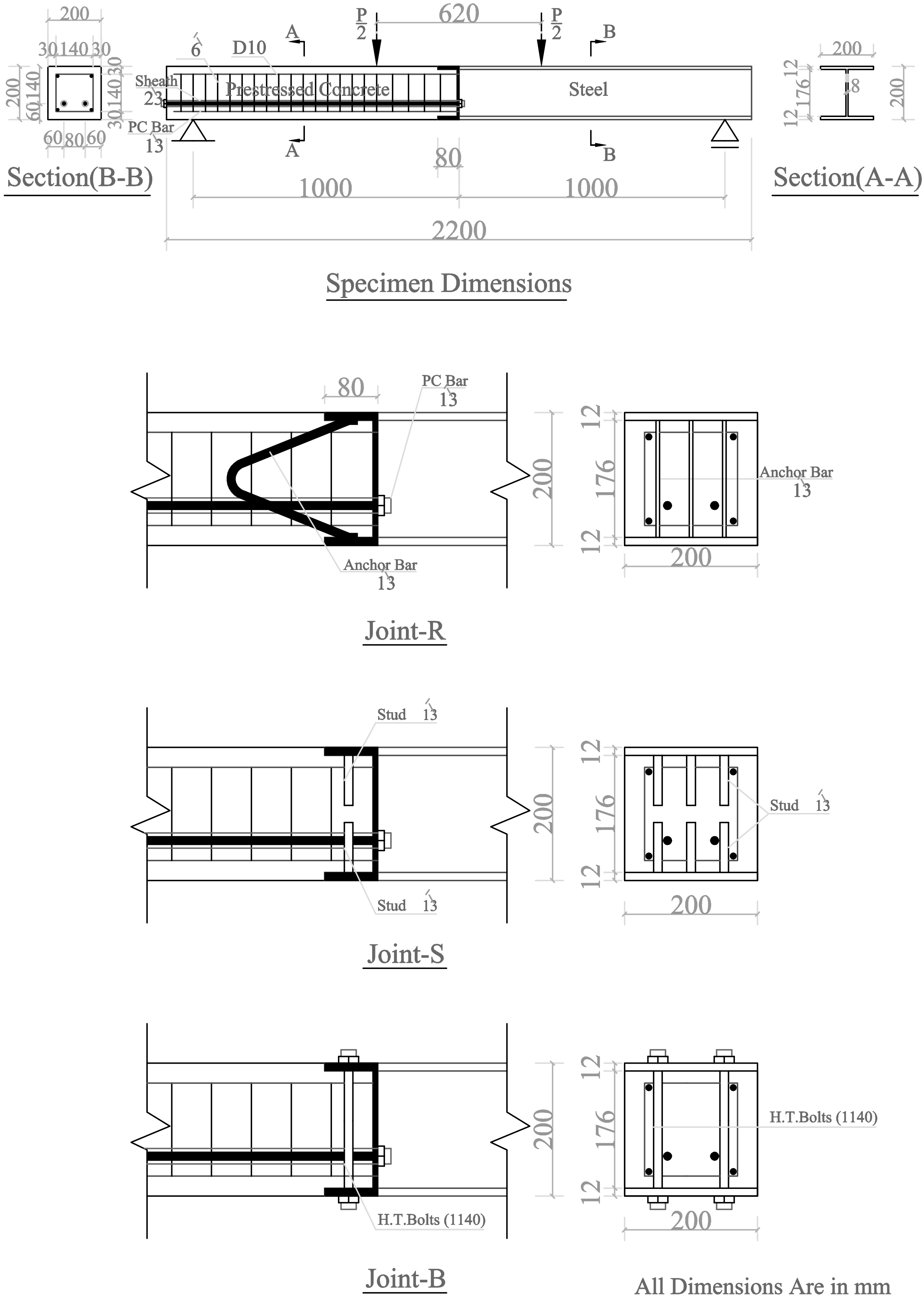
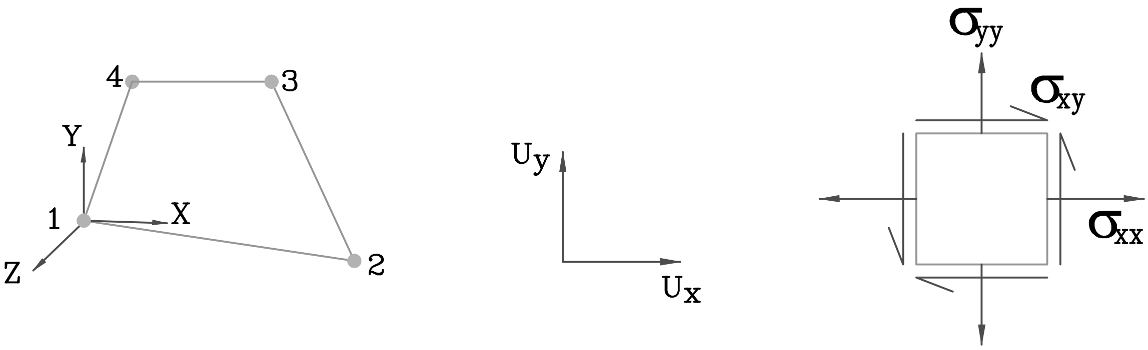
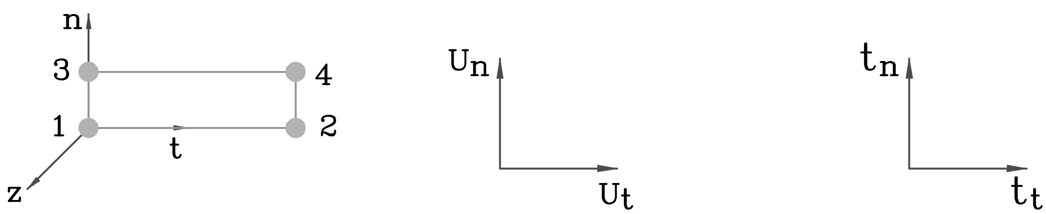


Fig.(2) Mixed Steel-Concrete Beam Specimens with Different Mechanical Joints (Hino 1984 and Hino 1985).



(a) Topology (b) Displacement (c) Stress

(i) Four Nodes Quadrilateral Elements



(a) Topology (b) Displacement (c) Tractions

(ii) Linear Line Interface Elements

Fig. (3) Quadrilateral and Interface Elements

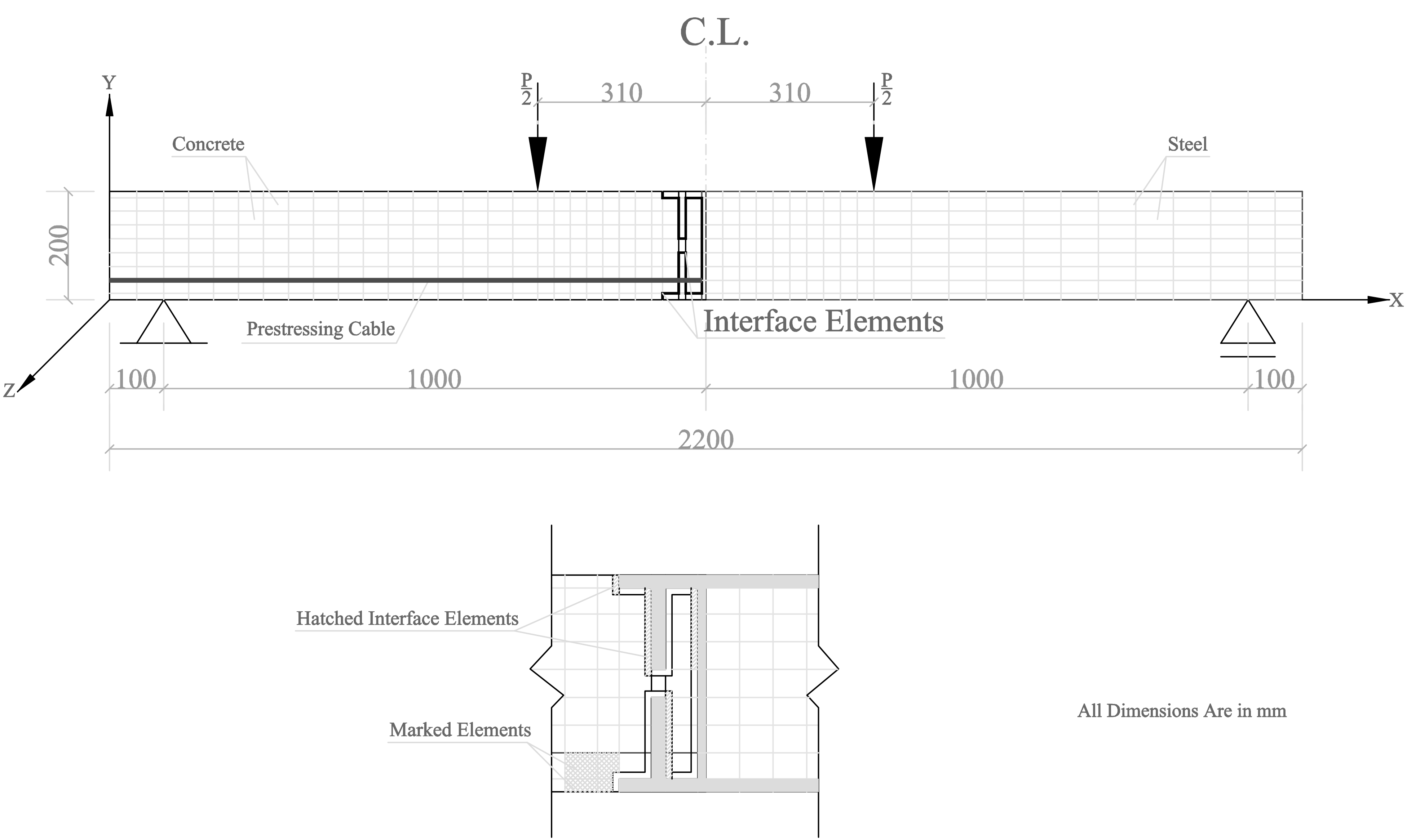


Fig.(4) Finite Element Idealization of Joint-S

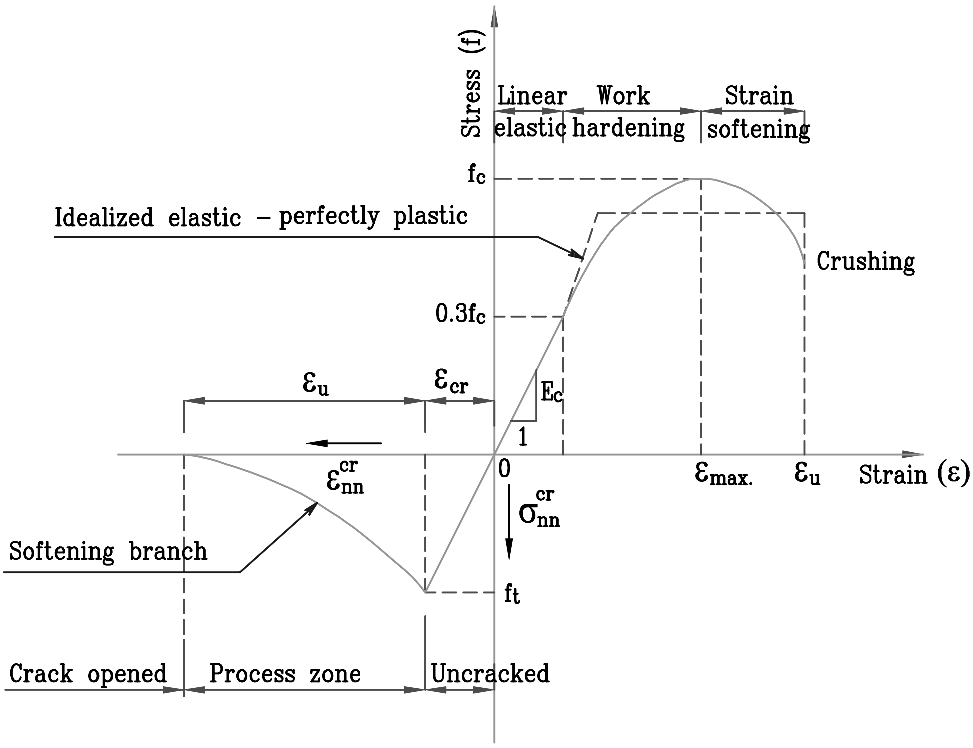


Fig. (5) Uniaxial Stress–Strain Curve for Concrete Elements

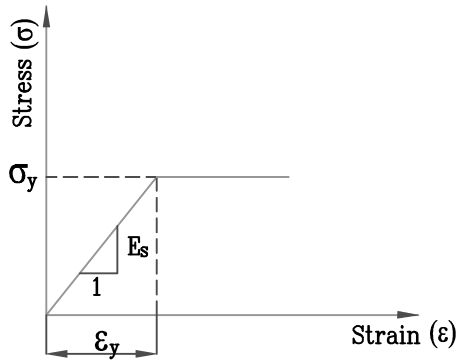


Fig. (6) Idealization of Stress–Strain Curve for Steel Elements and Reinforcing Steel Bars

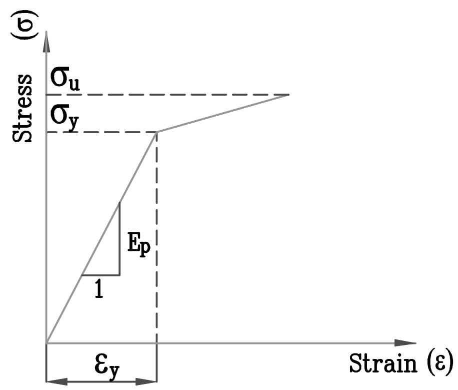


Fig. (7) Typical Stress–Strain Curve for Prestressing Steel

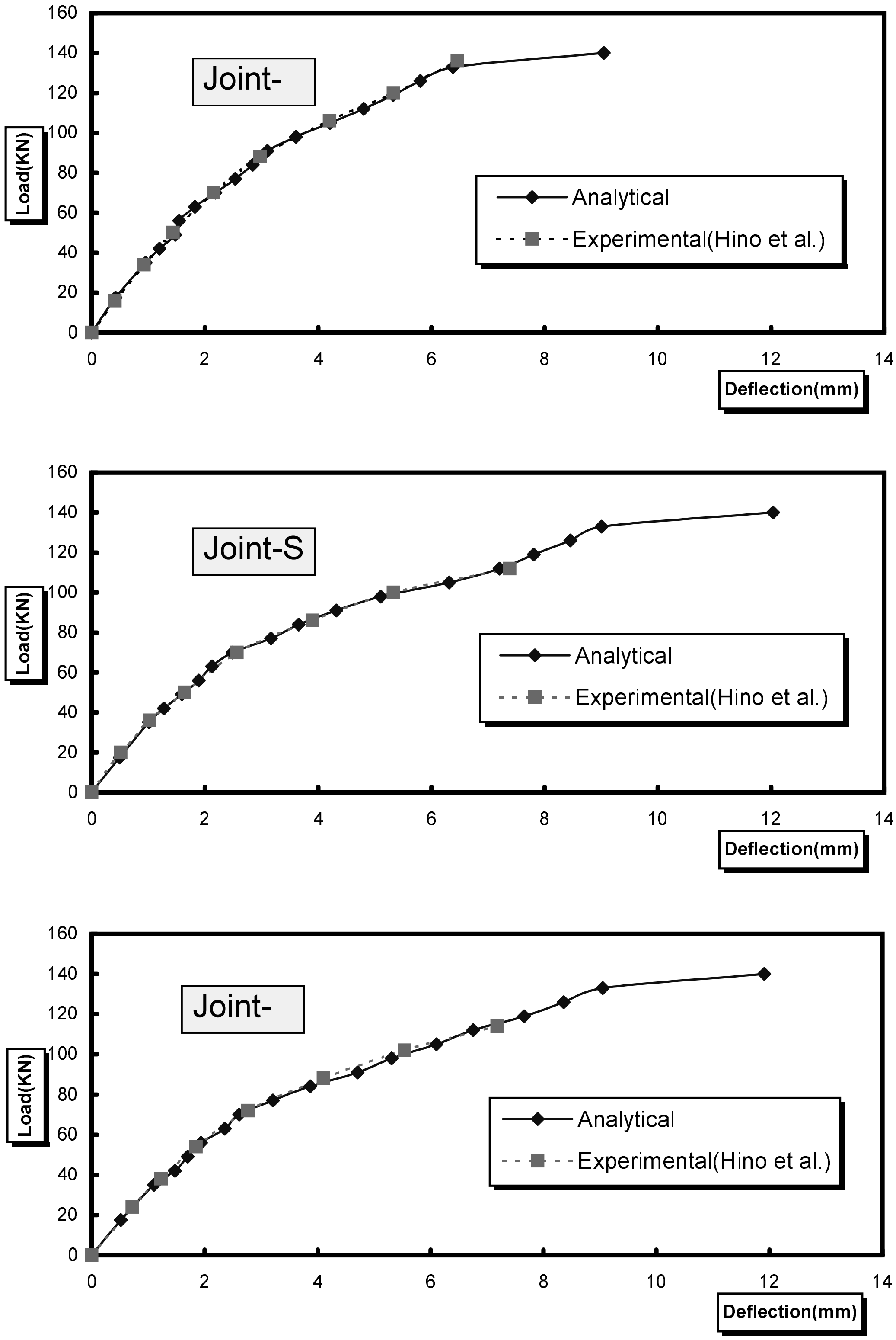


Fig.(8) Analytical and Experimental Load-Deflection Curves at Mid-Span

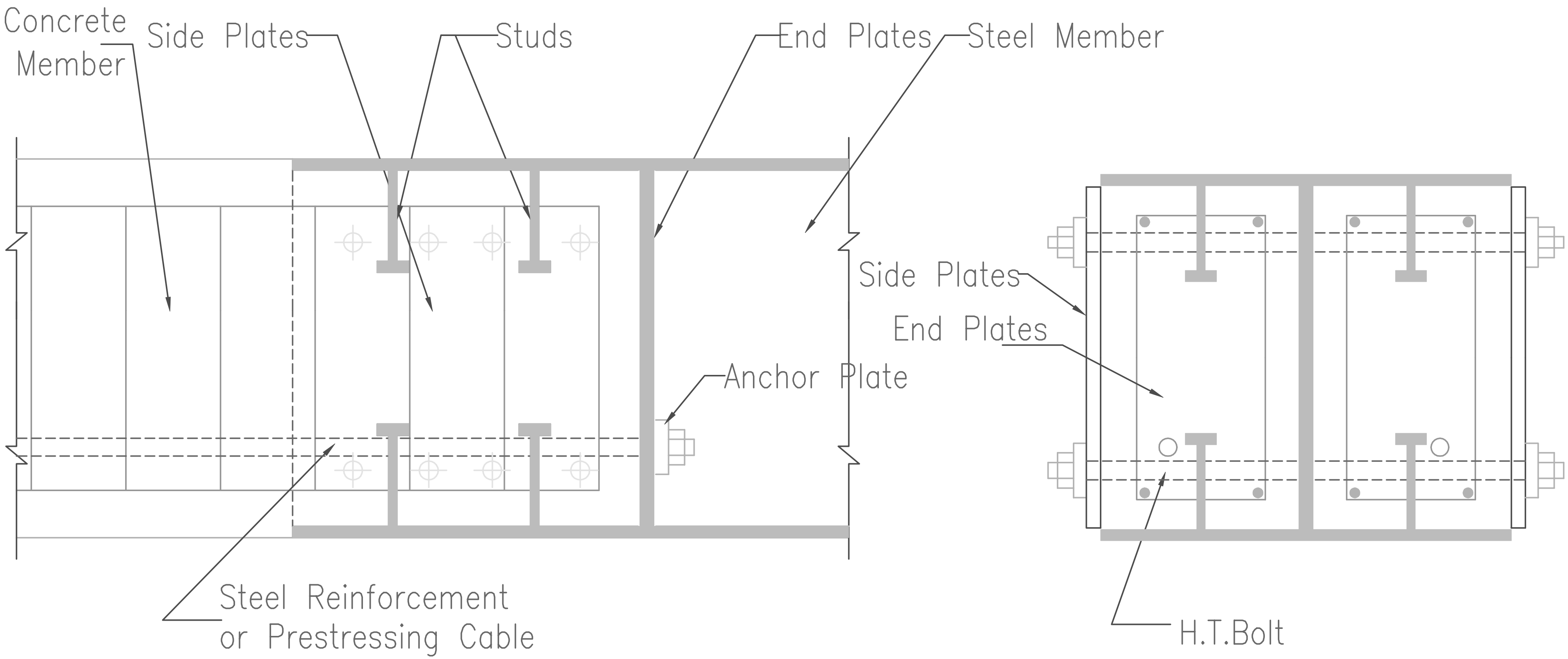


Fig. (9) Proposed Mechanical Joint