

Title: **Structural Performance of I-Tech Composite Beam Steel with Web Openings**

Authors: Kwang Ryang Chung, Dong Yang Structural Engineers
Young-Kyu Ju, Daewoo
Sung-Chul Chun, Daewoo
Dae-Young Kim, Daewoo
Do Hyun Kim, Korea University
Sae-Dae Kim, Korea University

Subject: Structural Engineering

Keywords: Composite
Shear
Structure

Publication Date: 2003

Original Publication: CTBUH / CIB Kuala Lumpur 2003 Conference

Paper Type: 1. Book chapter/Part chapter
2. Journal paper
3. **Conference proceeding**
4. Unpublished conference paper
5. Magazine article
6. Unpublished

© Council on Tall Buildings and Urban Habitat / Kwang Ryang Chung; Young-Kyu Ju; Sung-Chul Chun; Dae-Young Kim; Do Hyun Kim; Sae-Dae Kim

STRUCTURAL PERFORMANCE OF I-TECH COMPOSITE BEAM STEEL WITH WEB OPENINGS

YOUNG-KYU JU, SUNG-CHUL CHUN, DAE-YOUNG KIM

Daewoo Institute of Construction Technology, Suwon, South Korea

DO-HYUN KIM, SANG-DAE KIM

Department of Architectural Engineering, Korea University, Seoul, South Korea

KWANG-RYANG CHUNG

Dongyang Structural Engineers, Seoul, South Korea

Abstract

The classical composite beam, which consists of steel beam with concrete slab, is widely used in Korea due to its simple construction, fewer man hours and no formwork. Since the city area is limited, the height of a story is very important for the residential building in central city. However the height of the composite beam is deeper than the reinforced concrete beam. In this paper, a newly developed composite beam is proposed and experimentally explored via simple beam tests. The proposed composite beam is named iTECH (Innovative, Technical, Economical, and Convenient Hybrid) beam. iTECH has an asymmetric steel assembly with web openings, where the top plate is welded on the top of inverted structural tees cut as "honeycomb" style. The steel assembly is fabricated in the factory and both sides of the web and the slab are filled with cast-in-site concrete. To apply iTECH in practice, its shear and flexural capacities will first have to be evaluated through experiment. From the results of this research, iTECH beam is expected to be properly used as the shallow beam system for high-rise residential buildings.

Keywords: Tall buildings, Composite Beam, iTECH, Experiment, Shear Performance

1. Introduction

Even though the classic composite beam consisting of a steel beam with concrete slab has an added advantage of good workability[KIA,2001], it has several disadvantages. For one, the upper flange of its steel section does not have the structural capacity at the positive moment region. Thus, its shear stud should be set up at the site on top of the upper flange, with the fireproofing material covering the exposed steel surface [Naccarato,1999]. In addition, the composite beam is deeper than the reinforced concrete beam. Thus, high-rise commercial and residential buildings need alternative beams with lower stories. This is especially critical, since the height of a story is a significant factor in commercial and residential buildings in restricted city areas[Kim,2001]. Moreover, environmentalism is a growing issue in Korea. Specifically, fireproofing of the steel part has to be reduced or eliminated.

The Slim Floor was developed to minimize story height [ECCS,1995]. It is now widely used in Europe. The general form of this structural system consists of fabricated steel beams and a deep deck. Since the concrete is placed between the upper flange and the bottom flange, the Slim Floor gives one hour or one and half hour fireproofing; thus, additional fireproofing material is no longer required. In the USA, the flex-frame is used for lower story composite beam system [Mullett,1998]. The general form of this system consists of fabricated steel beams with web opening called D-section, as well as a deep hollow core precast plank. Since precast slab is placed at the bottom flange of the D-section, workability is acceptable. Like the Slim Floor, it also provides one hour fireproofing and does not require additional fireproofing. However, the beam-column is connected with pin connection and limited to the moment resisting frame.

In the conventional composite beam with an H-shaped steel, the structural efficiency of the top flange decreases as the neutral axis shifts towards the top flange of the steel beam [Park,1999]. Thus, the inverted T-shaped composite beam without a top flange was developed [Daewoo,2000;Viest,1997]. In addition, the iTECH beam was proposed to improve the performance of the inverted T-shaped beam. The shear transfer between the asymmetric structural steel and the concrete slab was obtained through bonding and bearing. Likewise, the •-type channel was placed on top of the bottom flange to support the deck. The web with the opening integrates the concrete beam and the asymmetric steel. Fig.1 shows the concept of iTECH beam. The composite action and structural capacity of the proposed composite beam were verified through experiments and analyses. Simple beam tests such as the flexural test and the shear test were performed under monotonic loading.

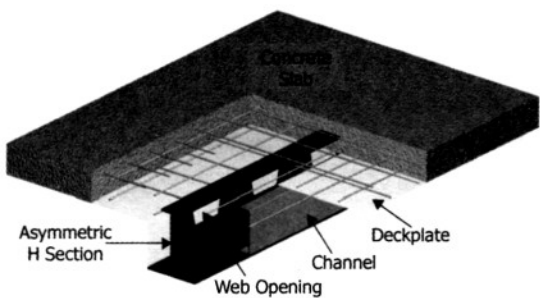


Fig.1 Concept of iTECH beam

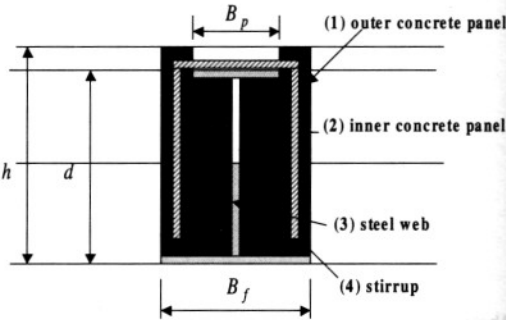


Fig.2 Components for the shear force mechanism

2. Shear Tests

2.1 Shear Resistance Components

Fig.2 shows the shear force components of the iTECH beam. Such force is assumed to be resisted by four components; the outer concrete panel, inner concrete panel, steel web with openings, and stirrup. Thus, the shear capacity of the iTECH beam is calculated as follows:

$$V = V_{co} + V_{ci} + V_w + V_s \tag{Eq.1}$$

where V_{co} , V_{ci} , V_w , and V_s are the shears corresponding to the outer concrete panel, inner concrete panel, web, and stirrup, respectively [Oehlers,(1995);Bugeja,(2000)].

2.2 Specimens and Setup

Fig.3 shows the shear tests conducted to investigate the effect of the web, concrete, and stirrup on the shear capacity of the iTECH beam. Four specimens were tested in order to determine the contribution of each component to the shear strength capacity. Table 1 shows the details of the specimens. One-point loading test was selected to obtain the shear between the center and the end of the specimen. Likewise, the monotonic load was applied under load control before yielding and displacement control after yielding.



Fig.3 Setup for shear tests

Table 1. Specimen details

Specimen	S-C2S1	S-C2S0	S-C1S0	S-C0S0
Slab thickness	125mm	125mm		
Slab width	246mm	246mm	246mm	
Stirrup	HD10@120			
Structural tees	CT 246×249×8×12:88mm from the bottom flange to the web opening			

2.3 Materials Properties

The average concrete compressive strengths at the test date were 30.1 MPa and the measured yield strengths of re-bar and steels were 398.2 MPa (D13), 280.0 MPa (flange of structural tees) and 249.4 MPa (t=18mm of steel plate), respectively.

2.4 Test Results

Fig.4 shows the load-displacement relationships of the specimens. The analysis based on the Korean Code[AIK,1997] and AISC-LRFD [AISC,1994] revealed that S-C0S0 i.e is the bare steel section has a yielding load close to the calculated load. However, the ultimate load was 1.81 times greater than the analysis. Similarly, the analysis results of S-C1S0, S-C2S0, and S-C0S0 were close to the test results hence indicating that shear can be calculated through theoretical analysis.

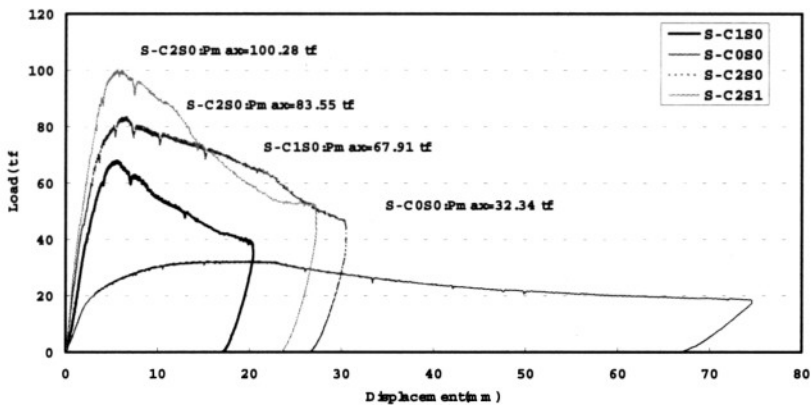


Fig.4 Load-displacement relationship for shear specimens

Table 2 compares the test results and the analyzed values. The contribution of the inner concrete in the test was 6% greater than its contribution in the analysis. On the other hand, the test results for the outer concrete showed a higher value of 58%. The inner part increased was due to restraining by the outer concrete. However, the maximum capacity was not reached for the stirrup. Moreover, the load rapidly decreased after yielding because the shear of the inner concrete was not well transferred to the outer concrete due to the varying strain rate. The top and bottom flanges restrained the inner concrete, while only the top flange restrained the outer concrete. Therefore, the design equation of iTECH beam included only the web and the inner concrete as shear resisting components (Fig.5). The outer concrete was reserved as marginal capacity. The shear force of iTECH is calculated as follows:

$$V = V_{ci} + V_w$$

Eq.2

where V_{ci} and V_w are the shears corresponding to the inner concrete panel and the web, respectively.

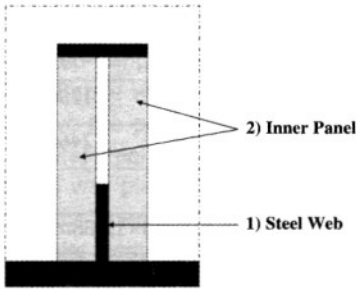


Fig.5 Shear force components for the design equation

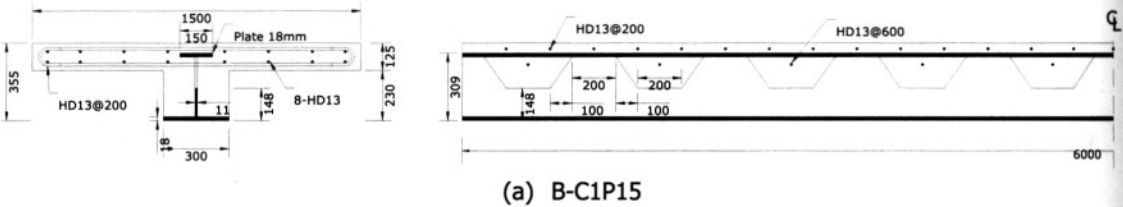
Table 2. Comparison of the test results and analyzed values

Specimen	Ultimate shear (Test)	Steel Web	Inner Concrete	Outer Concrete	Stirrup
S-C0S0	32.34 tonf	32.34 tonf			
S-C1S0	67.91 tonf	16.43 tonf	51.48 tonf		
S-C2S0	83.55 tonf	21.05 tonf	51.48 tonf	11.02 tonf	
S-C2S1	100.28 tonf	24.64 tonf	51.48 tonf	11.02 tonf	13.14 tonf
Theoretical Analysis		18.08 tonf	48.62 tonf	6.94 tonf	31.61 tonf
Ratio (Test/Analysis)		Larger than 100% for all cases	106 %	158 %	42 %

3. Flexural Tests

3.1 Design of Specimen

The full-scale T section specimens of 5m in length consisted of 3 beams; iTECH beam (B-C1P15), Slim Floor (B-Slim), and bare iTECH (B-C0P15), Fig.6. To ensure complete flexural behavior, the shear span to depth ratio was designed as 5.35. 2 points loads were applied, so the center region of 1,200mm was subjected to pure bending. The concrete compressive strength (f_{ck}) of 23.5 MP_a and the reinforcement yield strength (f_y) of 392 MPa were used for design purposes. D13 was placed for slab reinforcement. H-488×300×11×18 (SS400) and plate (t=18mm, SS400) were used for steel member. The transverse reinforcements of slab were placed through web opening for B-C1P15 and web hole of 30mm in diameter for B-Slim. Although the transverse reinforcements were not required for the strength of specimens, they were placed according to the limitation of BS 5950: Part 3 Sec. 5.6.3[BSI, 1990] to improve the slab integrity and especially the longitudinal shear strength.



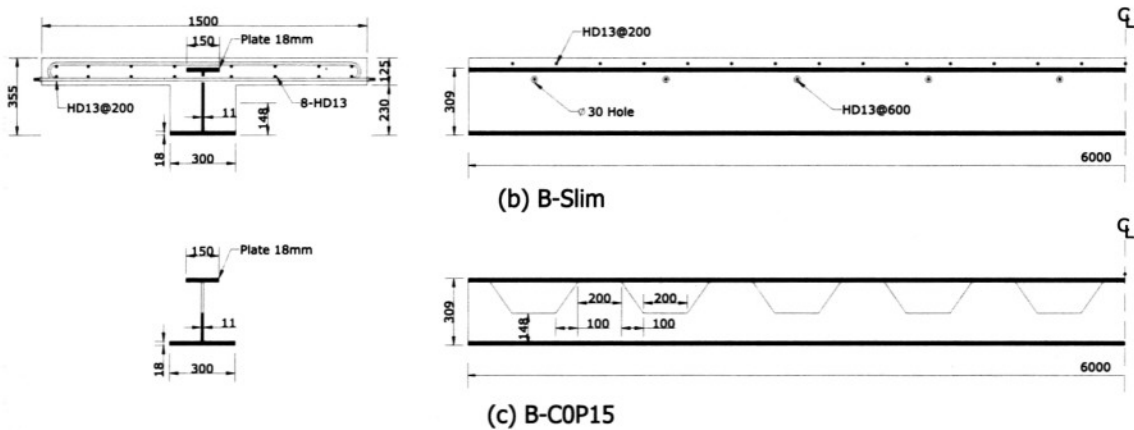


Fig.6 Details of Specimens

3.2 Strength Design

The yield strengths were designed in the same method of the general flexural member based on the complete composite action. But the ultimate flexural strengths could be divided into 2 types. One (P_{nf}) was based on the complete composite action and the other (P_{np}) on the partial composite action (Fig.7). P_{nf} was calculated, assuming that the strain of the extreme concrete was 0.003. P_{np} was obtained according to the strain distribution shown in Fig.7, assuming that the longitudinal shear force (F_s) between steel and concrete was constant as longitudinal shear strength (F_n). However, because the reduced concrete compression was transferred to steel flange, the difference between P_{nf} and P_{nf} was not significant (Table 3).

Table 3. Test Results

Specimen	Yield strength (P_y)			Ultimate strength (P_n)					Longitudinal shear force (F)			Ductility ratio (μ)	Slip load (P_s)	Buckling load (P_b)	Failure Mode
	P_{ye}	P_{yt}	P_{ye}/P_{yt}	P_{ne}	P_{nf}	P_{np}	P_{ne}/P_{nf}	P_{ne}/P_{np}	F_n	F_{ry}	F_{ru}				
B-COP15	173	198	0.88	240	241		1.00	1.00	-	-	-	1.7	-	17	Upper flange buckling
B-C1P15	536	536	1.00	730	625	624	1.17	1.17	1,509	1,548	1,578	10.1	573	588	Concrete Crushing
B-Slim	458	542	0.84	711	661	650	1.08	1.09	1,392	1,764	1,970	15.7	491	-	Concrete Crushing

Where subscript "e" denotes experiment and "t" denotes theory. Unit: tonf

While F_n for iTECH was the sum of bond capacity (F_{sb}) and bearing capacity (F_{bb}), F_n for Slim Floor was obtained from only bond capacity. In order, to keep completely composite to the ultimate state, higher longitudinal shear strength was required. But, after yielding of the tensile elements, the bond strength between steel and concrete may have been disintegrated. Therefore, it was a design target that the complete composite action was maintained only until serviceability state. There are several proposed equations on the bond strength and the bond area for composite member. In this research, Mullett's study[Mullett,1998] was adopted such as the bond strength f_{sb} was 0.6 MPa and the bond area was the perimeter of steel excluding the bottom face of the lower flange shown in Fig 8. The bearing strength (f_{bb}) was determined by KCI code.[KCI,1999]

The ultimate strength of a bare iTECH could be determined as the buckling load of flange before yielding of tensile steel. The buckling load of flange could be calculated according to AIK LRFD[AIK,1997] considering regarding that the upper flange is a compression member. The ultimate strength, ignoring buckling, was calculated based on the fully plastic analysis. The calculated strengths were summarized in Table 3.

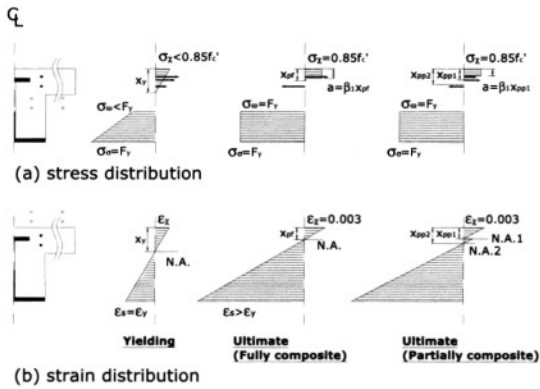


Fig.7 Strain and Stress Distribution

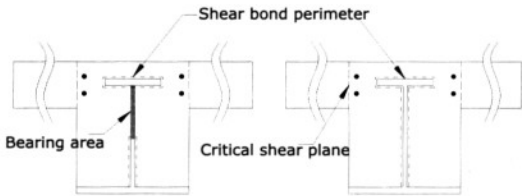


Fig.8 Bond and Bearing Area

3.3 Testing and Instrumentation

To prevent lateral torsional buckling, the lateral supports were installed at the reaction points and at 2 points 1,200mm from the center. The load was applied monotonically using 1,960 kN capacity actuator with loading beam. The displacement of center point and the slips of 7 points between concrete and lower flange were measured. And the strains of upper flange, slab concrete and re-bars were measured.

3.4 Flexural Behavior of B-C0P15

A typical flexural behavior was observed without lateral torsional buckling. The buckling of upper flange initiated at 169.5 kN and after the upper flange has completely buckled at 240.1 kN, the load was rapidly reduced. The lower flange did not yield. Fig.9 shows the relationship between load and displacement.

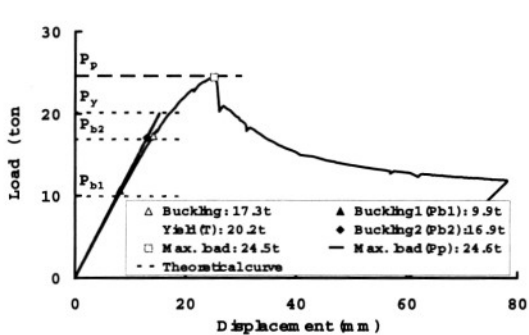


Fig.9 Load vs. displacement (B-C0P15)

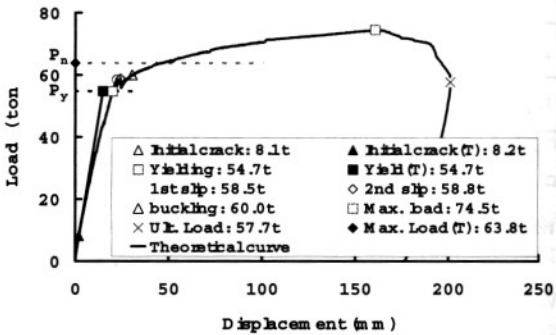


Fig.10 Load vs. displacement (B-C1P15)

The buckling strength depends on the effective buckling length. P_{b1} and P_{b2} in Fig.9 indicate the buckling strengths based on 600mm and 300mm of the effective length, respectively. Fig. 7(b) shows the buckling of upper flange. Based on the effective length factor (K) = 0.75 with buckling length 400mm (web opening length), the real buckling load can be predicted quite accurately.

3.5 Flexural Behavior of B-C1P15

A typical flexural behavior, in the sequence of [concrete flexural crack] • [tensile element yield] • [compressive concrete crushing], was observed. After yielding of the lower flange, the slip between steel and concrete occurred, and B-C1P15 was considered acting as partially composite. B-C1P15, however, failed with compressive concrete crushing, and the capacities of all structural elements were utilized. Judging from the measured strains of the upper flange it appears that the buckling of upper

flange was initiated at 588 kN after yield load. But, during test no symptom of buckling was observed and there was no special change in the relationship between load and displacement. In contrary to B-COP15 the upper flange was confined by concrete and contributed little to the ultimate strength. The buckling of the upper flange could not be perceived before peak load. The cracks occurred concentrically at 200mm spacing. The space and width of crack were wider than those of common RC flexural member.

The theoretical cracking and the yield strengths were very close to the experimental values, and the ultimate strength exceeded the calculated value by 17%. It is possible for iTECH to develop wide crack because there is no tensile re-bars and tensile force is resisted by CT steel alone. The 3 widest cracks within the pure bending region were observed during test. While the width of central crack was 0.15~0.17mm at 60% of yield load, which satisfied the limitation of allowable crack width for RC structure,[AIK,1995] the widths of right and left cracks rapidly developed and exceeded the allowable crack width of 0.3mm at the load of $0.6P_y$. This is due to the stress concentration at loading points. In real structure, the development of crack will be similar to that of the central crack. When the load exceeded the yield strength by 8%, slip suddenly occurred and the load was reduced. Soon the load was recovered and the slip steadily progressed. At peak load state, the maximum slip was 10.2mm. As soon as slip occurred, the stiffness declined and the displacement increased rapidly. As previously mentioned, B-C1P15 with a partial composite action failed with compressive concrete crushing.

3.6 Flexural Behavior of B-Slim

B-Slim behaved similarly to the flexural behavior of B-C1P15. Because the design longitudinal shear strength (F_r) was far less than the required value (Table 3), the slip between steel and concrete took place slightly before yield. Before slip, B-Slim behaved as a complete composite member and failed with compressive concrete crushing despite slip, not bond failure.

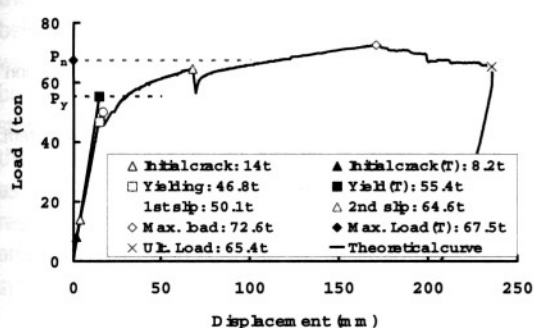


Fig.11 Load vs. displacement (B-Slim)

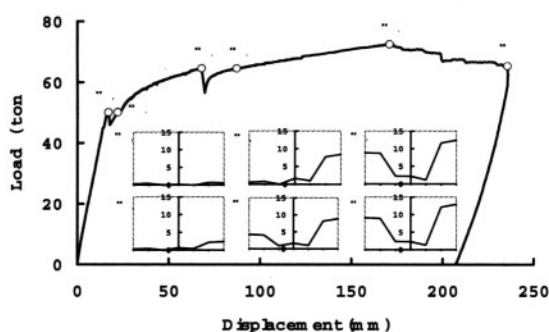


Fig.12 Development of Slip (B-Slim)

Slip preceded the yield of lower flange, so B-Slim yielded earlier than expected i.e at 84% of design yield load. However, the ultimate strength exceeded the design value by 8%. Fig.12 shows the slip development. While the slip of B-C1P15 steadily developed, the slip of B-Slim discretely developed twice. When each slip occurred, the load was considerably reduced.

Conclusions

Monotonic loading tests were conducted to evaluate the shear and flexural behavior of iTECH beam which was developed to reduce story height and to improve constructability. Seven specimens were tested and the findings summarized as follows:

- (1) The factors that contributed to the shear strength of iTECH were the steel web, the inner concrete panel, and the outer concrete panel. It was proven that the shear stirrup contributes slightly to the shear strength. However, the strength contribution by the outer concrete panel is excluded in the

design equation for a conservative design and convenience. Therefore a the design equation involving the steel web and inner concrete panel is proposed.

- (2) ITECH beam is designed as a full composite beam during the service load state and as a partial composite beam after the yield. The flexural test results show that ITECH behaved properly, as expected.
- (3) Because the longitudinal shear force after the yield was kept constant over the design strength, ITECH failed from concrete crushing without bond or local failure. Therefore, every structural element could be efficiently utilized.
- (4) In the erection stage, the reasonable design criterion is the buckling of the top flange. The effective length coefficient was found to be 0.75.
- (5) From the results of this research, ITECH beam is expected to be of potential use as a shallow beam system for high-rise residential buildings

Acknowledgements

We express our sincere gratitude to the concerned people of Haesung Kigong Ltd for the sustainable support.

References

- Architectural Institute of Korea (1997), *Ultimate State Design of Steel Structure*.
- Architectural Institute of Korea (1995), "Code for Design of Reinforced Concrete Structure".
- America Institute of Steel Construction (1994), "Manual of Steel Construction : LRFD".
- Bae, K.W. (2000). Development of Semi-Slim Floor Using Deck Plate. Presented on Technical Seminar on Composite Deck for Less Story Height, pp.3752.
- BSI. (1990). BS 5950: Part B: Appendix E. Simplified Method of Calculation for Beams with Shelf Angles.
- Bugeja M.N, J.M. Bracci, and J.P. Moore Jr. (2000). Seismic behavior of composite RCS frame systems. ASCE, Journal of Structural Engineering. April, pp.429-436.
- Daewoo Institute of Construction Technology (2000), *Technical Report of TEC Beam (1)*, (in Korean)
- ECCS. (1995). Multi-Storey Buildings in Steel: Design Guide for Slim Floors with Built-in Beams.
- Huber, G. (2000). Nonlinear Calculations of Composite Sections and Semi-Continuous Joints. Ernst & Sohn.
- Ju Y. K., Kim D. Y., Chung K.R., and Kim S. D. (2001), "Composite Action of the A-TEC Beam with Asymmetric Steel Section", Journal of the Architectural Institute of Korea, Structure & Construction Section, Vol. 17, No. 9, Sep., pp. 49-56.
- Kim, S.D., Y.K. Ju, and K.R. Chang. (2001). An experimental investigation on the structural behavior of TEC beam system. International Journal of Steel Structure, Vol.1 (3): 235245.
- Korea Concrete Institute (1999), Structural Design of Concrete, (in Korean)
- Korea Institute of Architects. (2001). Steel Apartments in Korea.
- Mullett, D. L. (1998), *Composite floor system*, Blackwell science Ltd.
- Naccarato, P. A. (2000), *Low Floor-to-Floor Heights*, Modern Steel Construction.
- Naccarato, P. A. (1999), *New Alternative to Flat Plate Construction*, Modern Steel Construction.
- Oehlers, D.J. and M.A. Bradford. (1995). Composite Steel and Concrete Structural Members: Fundamental Behavior. Pergamon Press.
- Park K. H. (1999), "An Experimental Study on Composite Behavior of TEC Beam", Thesis of M.E., Korea University.
- Viest, I.M. and J.P. Colaco. (1997). Composite Construction Design for Buildings, ASCE.