DESIGN OF HAUNCHED COMPOSITE CONNECTIONS FOR LONG SPAN BEAM CONSTRUCTION

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ABSTRACT

One of the structural options for beam spans beyond 15m is the haunched beam. By developing continuity at the supports, beam moments and deflections are reduced and this can lead to overall economy by enabling the use of shallower and lighter beam. This paper investigates the behavior of steel-concrete composite haunch connections. Experiments are carried out to study the moment-rotation characteristics of the connections and ultimate moment capacity of the composite sections. Design implications related to composite haunched beams are discussed.

INTRODUCTION

The authors have developed an advanced inelastic analysis model for analyzing the behavior of three-dimensional semi-continuous frames [Liew et al., (1)]. The analysis and design methodology has been verified against test results involving full-scale testing of frames and connections [Liew et al., (2)]. Recent work has been focused mainly on composite frames and their connections [Liew et al., (3)]. Experimental work is currently on going to verify the capability of the analysis model for analyzing building framing systems including the effects of composite beams and connections [Liew et al. (1), (3) & (4)].

In recent times, the demand for long-span and column-free space in buildings has necessitated further research into the behavior of haunched beams since they are considered to be an efficient and economical form for long span construction. Haunched beams are designed by assuming a rigid moment connection between the beams and columns [Lawson and Rackham, (5)]. Depth and length of a haunch may be chosen to enable an economical method of transferring moment into the column and in reduction of beam depth to a practical minimum. Haunched composite beams in which steel beams are designed to act in conjunction with concrete slab of definite width could result in shallow beams, provide a long unobstructed space for services and increase in speed of construction.

Past work on haunched beams focused mainly on steel haunched connections under negative moment. Design methods have been proposed for continuous composite beams, but the hogging beam section and connections are designed as non-composite [Lawson and Rackham, (5); Boswell, (6)]. The object of this paper is to report on the experimental results obtained from sub-assembly tests of composite haunch beams. The experimental program is presented and the results for ultimate moment capacity of the tested haunched connections are given. A design method consistent with the Eurocode approach for designing continuous composite beam is proposed [Eurocode, (7)].

SUB-ASSEMBLY TESTS

Five test specimens were chosen to study the effects of haunch length and amount of reinforcement in the slab on the behavior of composite haunched beams. Each specimen consists of two cantilever haunch beams subject to concentrated load applied at the beam ends, as shown in Fig. 1, to simulate an internal joint of a braced frame. The depth of the haunch was chosen equal to the depth of the steel beam. The length was varied from 250 mm to 968 mm, which are equivalent to 3.12%, 5.41%, 8.84% and 12.10% of the beam span. Full depth stiffeners were provided at both sides of the beam web at the haunch tip to prevent lateral-distortional buckling of the beam under negative moment. The details of the test specimens are given in Table 1. Specimen H1 was plain steel specimen whilst the remaining four specimens consist of steel beams act in composite with the floor slab in which sufficient shear studs were provided to develop full composite action.

Table 1 Details of Test Specimens

Specimen	1		2		3		4		5	
Connection	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10
Reinforcement %	0	0	1.34	1.34	2.62	2.62	1.34	1.34	2.62	2.62
Haunch Depth, mm	250	250	250	250	250	250	250	250	250	250
Haunch length, mm	250	433	250	433	250	433	707	968	707	968
Shear Studs per group	Nil	Nil	1	1	2	2	1	1	2	2
Total number of shear studs per beam	Nil	Nil	13	13	26	26	13	13	26	26

Tensile tests were carried out to determine the yield strength and ultimate strength for beams and columns. Similar tests were carried out on the reinforcement bars used in the test specimens and the average values of yield strength and ultimate strength are summarized in Table 2.

Table 2 Properties of steel and reinforcement bars obtained from tensile tests

Item	Diameter (mm)	Yield strength (N/mm^2)	Ultimate Tensile strength (N/mm^2)	Area (mm^2)
Steel Beam	-	309	414	-
Steel Column	-	328	498	-
T20 steel bar	20	565	693	314
T16 steel bar	16	484	584	201
T10 steel bar	10	489	581	79

Figure 1 Typical test Set-up

INSTRUMENTATION AND LOADING PROCEDURE

Inclinometers were placed along the centerline of beam section to measure section rotations. Displacement transducers were used to measure the relative displacements so that the joint rotation can be calculated**.** Electrical resistance strain gauges were used to measure strain in steel so as to monitor yielding and to determine the failure modes. They were placed at top and bottom of beam flanges near the column flange, at the haunch toe and reinforcement bars. Besides, strain gauges were also placed on some bolts connecting the beams to column flange. This was intended to find out the tensile forces in the bolts at each of the load steps.

The entire load application was performed in three stages. In the first stage, load was applied until the first crack was observed in concrete and, in the second and third stage load was increased up to 60% and 90% of the estimated ultimate load, respectively. This process of loading helps to obtain the initial stiffness of connection and to compare the unloading stiffness at different loading stages. In the final stage, loading was continued until the failure of the specimen.

As mentioned earlier each of the specimens consisted of two haunched connections, one with shorter haunch length and the other with longer haunch length. Therefore, the load application and other measurements were monitored separately. Load was applied in equal increment to each of the haunched beam at the initial stages of loading. Once the weaker beam attained the load close to the failure load, care was taken to balance the load on both beams. When the weaker beam attained its maximum capacity, the load on that beam was maintained at that level whilst the load on the stronger beam was continued until it reached its failure.

PREDICTION OF ULTIMATE MOMENT

Haunch connection without slab reinforcement

Assuming that the bolt will fail in tension and only one tension bolt row is used, the full tension capacity of the bolts is

$$T = R_b < R_{hf}$$

Taking moment about the haunch flange, the moment resistance can be evaluated as

$$M_{hu} = R_b \text{ x } (D - D_b + D_h - T/2)$$

Haunch connection with slab reinforcement

It is found that the plastic neutral axis (PNA) lies in the haunch flange when

$$R_r + R_b < R_{hf} + R_{HW}$$

Thus, moment can be determined as follows:

$$y_c = \frac{R_r + R_b - R_{hf}}{1.2\, p_y\, t_{hw}}$$

$$R_{hw} = 1.2\, y_c\, p_y\, t_{hw}$$

$$M_u = R_r(D_r + D + D_h - \frac{T_{hf}}{2}) + R_b(D - D_b + D_h - \frac{T_{hf}}{2}) - R_{hw}(y_c + \frac{T_{hf}}{2})$$

where M_u is moment capacity of composite haunch connection, p_y design strength for steel, R_b bolt capacity in tension, R_{hf} haunch flange capacity, R_{hW} haunch web capacity, R_r tensile force in reinforcement, t_{hw} thickness of the haunch web, T_{hf} thickness of haunch flange and y_c distance from the top of haunch flange. In an end-plate composite connection, the first tension bolt row seldom achieves its full tension capacity. In haunched composite connection, the first bolt row always achieve its yielding capacity. This is because the PNA hardly lies above the level of the first bolt row. This has been observed in one of the connections tested (H8) in the current series. The composite beam moment capacity at the tip of the haunch was obtained based on the method given in [Eurocode, (7)] for section under negative bending.

RESULTS AND DISCUSSION

Ultimate moment obtained from the experiments along with those predicted by the present method for all the test specimens are summarized in Table 4. Also, the experimental values are compared with the predicted results, which shows a good prediction within 10% margin.

Effect of Slab Reinforcement Ratio

Figure 2 compares the load-displacement curves obtained from specimens H2, H4 and H6 which have same haunch depth (D_b) and length ($2D_b$), but of different slab reinforcement percentage of 0%, 1.34% and 2.62%, respectively. Higher percentage of reinforcement in the slab shifts the failure from the steel connection to the haunched toe composite section. Failure of H2 connection was triggered by tensile fracture at the bolt thread. Failure of H4 occurred at the haunch toe in which the composite beam section is almost fully yielded, and the compression beam flange at the point of intersection with the haunch toe has buckled inelastically. H6 was the same in all respects as the specimen 2 and 4 except that the concrete slab was reinforced with 10 numbers of T20 deformed bars. Failure occurred at the haunch toe, as shown in Fig. 4, where the composite beam section in negative bending was almost fully yielded in compression. Further increase in reinforcement will not yield significant improvement of load carrying capacity since the limit of resistance for the steel section in compression has been reached with plastic neutral axis shifted to the concrete slab.

Table 4 Summary of Test Results

Specimen	1		2		3		4		5	
Connection	H1	H2	H3	H4	H5	H6	H7	H8*	H9	H10
Ultimate Load (kN)	138	117	162	181	222	241	258	312	306	NA
M_{exp} at haunch toe	214	160	251	248	344	330	282	260	334	NA
M_{exp} at haunch Con	249	211	291	327	399	434	464	562	550	NA
Failure Mode	Con.	Con.	Toe	Toe	Toe	Toe	Toe	Con.	Toe	NA
M_{pred} (kNm)			255	255	319	319	255	533	319	319
M_{exp}/M_{pred}			0.98	0.97	1.08	1.03	1.1	1.05	1.05	NA

*Failure of Specimen H8 occurred at the haunch heel. The values shown in the table are those corresponding to haunch heel.

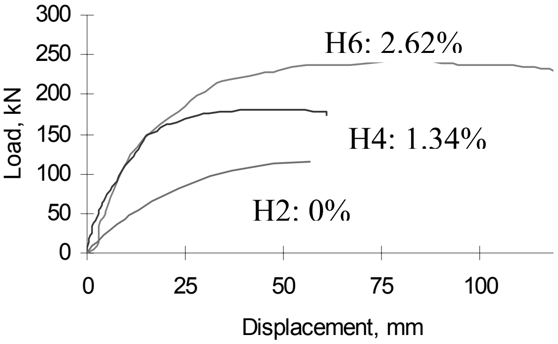

Fig. 2 Effect of reinforcement ratio: haunch depth = D_b; length = $2D_b$.

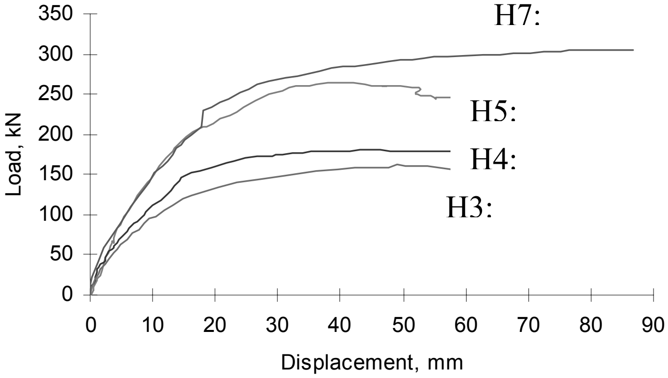

Fig. 3 Effect of haunch length: haunch depth = D_b; reinforcement ratio= 1.34%

Effect of Haunch Length

Specimens H4, H7 and H8 have been tested as parts of the specimen H3 except the haunch lengths were chosen approximately equal to two times the depth as in H4, three times the depth as in H7 and four times the depth as in H8. The reinforcement in the slab was kept the same as in specimen 2. Figure 3 compares the load-displacement curves obtained from these specimens. For H4 and H7, failure moment for this connection occurred at the haunch toe. For H7, the ultimate capacity of composite section (282 kNm) at haunch toe section was close to the calculated plastic capacity (255 kNm) by Eurocode 4. Connection H8 is the same as H4 except that the haunch length in this case was 968 mm or 12.10 % of an 8-m span beam. Failure occurred at the haunch heel near to the connection as shown in Fig. 5. Failure moment for this connection was found to be 562 kNm, which is close to the predicted value of 533 kNm. The test results show that it is possible to control the failure mode by varying the haunch length and that longer haunch length shifts the failure from haunch toe to haunch heel.

Fig. 4 View after failure of H6

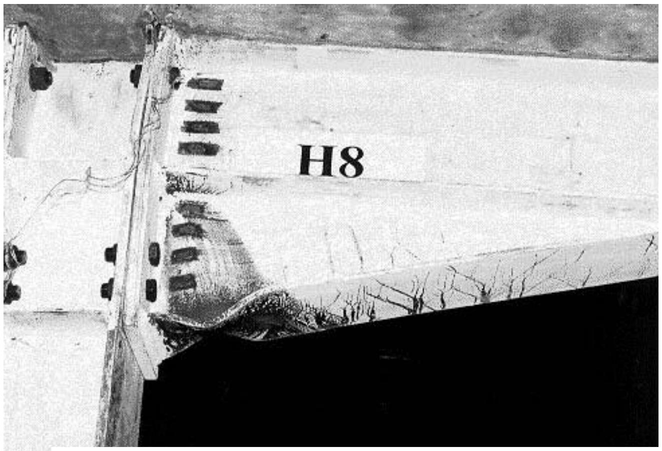

Fig 5 View after failure of H8

TESTING OF COMPOSITE HAUNCHED BEAMS

The purposes of the tests were to model a haunched composite beam within a braced multi-span and multi-story frame, and to investigate the likely redistribution of moments around the frame due to the formation of plastic mechanism in the beam. The load at collapse was compared with that obtained from plastic analysis hence the proposed plastic design method could be established.

The test setup of the composite haunched beam is shown in Figs. 6a&b. The beam is subject to two concentrated loads at the inner span and a point load at the tip of the end spans to simulate the continuous beam action. Four independent actuators were employed, two for the main beam and two for the cantilever beams. Plastic analysis and design methods were adopted. A plastic collapse mechanism was expected in the inner beam, while the columns were designed to remain elastic. This experimental set up is to test the inner span to its ultimate capacity. Thus, care had been taken to prevent failure at the beam-to-column connection at the cantilever beam by providing a stronger haunched connection.

The details of the beam specimens are summarized in Table 5. The beam capacities, based on the total loads applied to the beam at failure, are also reported in Table 5. Comparison of HB1 and HB2 shows that an increase in slab reinforcement from 1.34% to 2.62% leads to 11% increase of beam capacity. Plastic hinges form at the haunch toes follow by inelastic redistribution of forces until a plastic zone occurs at the mid-span. There was no sign of strength degradation even when the beam reached a very large displacement.

Comparison of HB1 and HB3 shows that increasing haunch length from 1.7D_b to 3.9D_b leads to 25% increase in beam capacity. For HB3, a wide plastic zone was first developed at the mid-span between the two load points followed by failure at the haunched connections. However, the connection failure occured only when the beam deflected to a very large extent. HB3 was designed to achieve the most optimum load carrying capacity in which the moment resistance of the haunched connections and composite beam could be reached simultaneously.

Table 5 Details and results of beam tests

Beam Specimen	HB1	HB2	HB3
Reinforcement, %	1.34 (8T16)	2.62 (10T20)	1.34 (8T16)
Haunch Depth, mm	250	250	250
Haunch Length, mm	433	433	968
Slab width, mm	1400	1400	1400
Slab thickness, mm	120	120	120
Shear studs per group	1	2	1
Beam Capacity (2P, kN)	540	604	674

B1, B2 and B3: 254 x 146 UB 37 kg/m and C1: 203 x 203 UC 60 kg/m.

DESIGN IMPLICATIONS

Composite haunched beams are designed in a similar manner to continuous beams of uniformed section. The critical sections for design are at the haunch toe, haunch heel or the haunch connection. The depth of the haunch may be selected to develop the required moment in the connection. The length of the haunch is selected to provide an economical design of the beam. The additional of reinforcement in the slab provides higher negative moment resistance to both the haunched connection and the haunch sections. The effect of composite action is to reduce the haunch depth for the same moment. However, large amount of reinforcement will result in an upward shifting of plastic neutral axis (PNA), and the steel section will be subjected to more compression. The result of this is that the available rotation capacity of the composite section is reduced. The test results show that the composite haunched connection is very rigid and the connection rotation is negligible. For all the composite connections (except H8) failure does not occur at the connection because the critical component is in the beam at the haunch toe. By providing a full depth stiffener at both sides of the web at the haunched toe, the haunched section is sufficiently restrained to prevent lateral buckling. There is sufficient rotation capacity at the haunched toe for a plastic mechanism to form in a beam. It should be noted that 'Plastic Analysis' requires only the ultimate moment and rotational capacities. As long as the section is able to resist the limit load and provide sufficient rotations, which allow moment redistribution, connection stiffness is not a requirement in a rigid frame analysis. This is evident from the tests conducted on three continuous haunched beams using the same haunch connections as reported in this paper.

Composite haunched beam can be designed economically for span-to-depth ratio ranging from 25 to 30. For span length beyond 30D, where D is the depth of steel beam and the slab, deflection and vibration become the main concern. Other innovative structural options needed to be devised to achieve the desired performance.

CONCLUSIONS

Experiments on composite haunch connections are described and results corresponding to ultimate moment capacity, and failure modes are presented. These connections are classified as a full strength rigid connection in accordance with Eurocode 4. It is confirmed by the test results that the measured moment capacity for all connections is larger than the plastic capacity of the beams and rotation in all tests was very small, less than 2 miliradian. Prediction by Eurocode 4 to estimate the ultimate capacity of composite hogging section is sufficiently accurate. Results show that observed moment capacity for the hogging section of the beams falls within 10 % of the predicted value. Haunch toe can be strengthened effectively by means of web stiffener to the full depth of the beam. However, the length of the haunch is limited to 12.10 % of the beam span. Experimental observations show that the failure is localized at the haunch toe section. Haunch length has no significant effect on rotation capacity and it is found that rotation at the ultimate capacity always falls within 30 to 45 miliradian. Increase in reinforcement from 1.34% to 2.62% does not reduce rotation capacity significantly but it increases the ultimate moment capacity of the composite section. Longer haunch length tends to shift the mode of failure to the haunch heel of the connection.

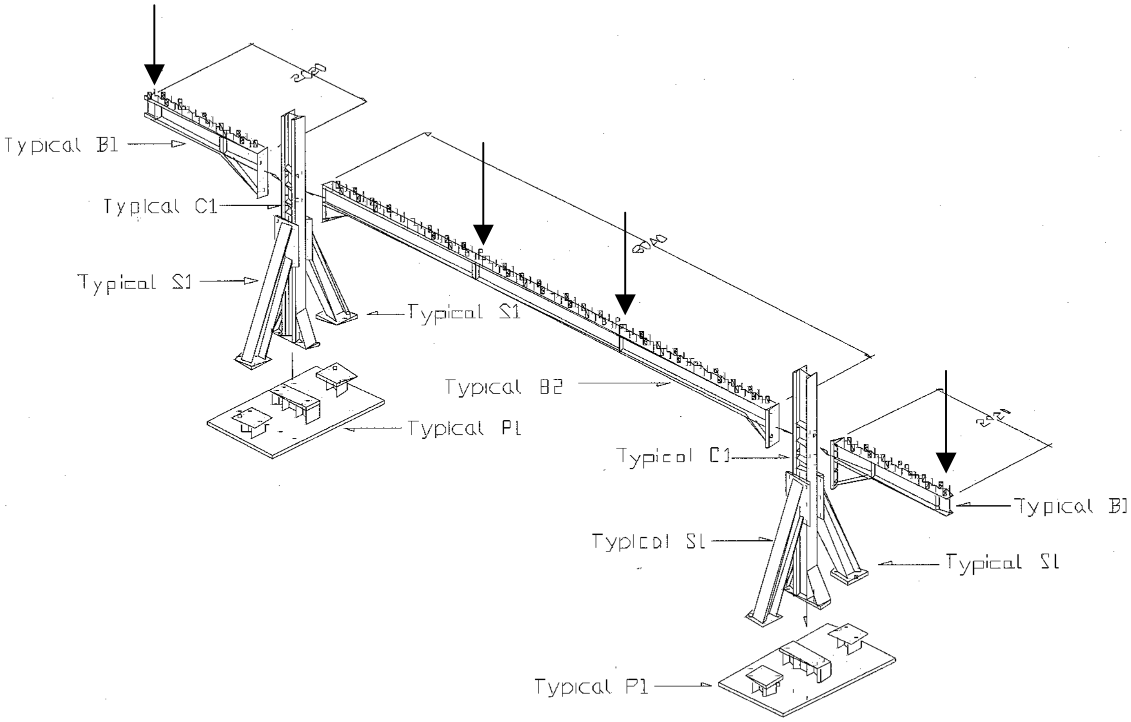

Figure 6a Test set up of composite haunched beam

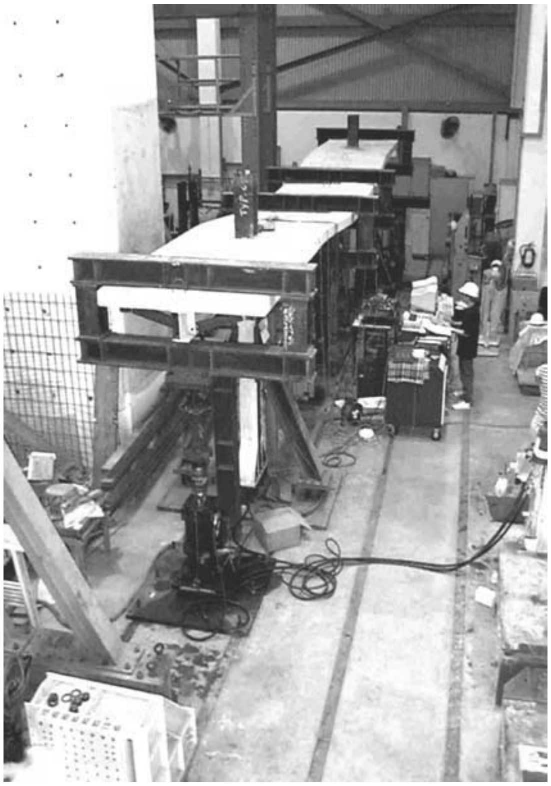

Figure 6b Testing of a typical composite haunched beam

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