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Experimental Studies of Nodes in Strut-and-Tie Models

Etude des régions nodales dans le cas de l'analogie du treillis

Verhalten von Knotenbereichen und Stabwerkmodellen

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SUMMARY

This paper presents the results of a series of tests in which the behaviour of the nodal regions used in strut-and-tie models (STM) was studied. The research program included the construction and loading to failure, of a series of dapped beams and two series of isolated node specimens which simulated CTT and CCT node portions of the dapped beams. The test results supported the use of the STM in detailing. They indicated that the commonly used approach for determining the required development for hooked and straight bars may be overly conservative for node design and showed the beneficial effect of confinement of the concrete in the node and around the tie bars.

RÉSUMÉ

Cet article présente les résultats d'une série de tests étudiant le comportement des régions nodales dans le cas de l'analogie du treillis. Le programme de la recherche incluait la construction et le chargement jusqu'à la rupture d'une série de poutres à décrochement d'extrémité, ainsi que l'étude de deux séries de nœuds isolés simulant les nœuds CTT et TTC de la poutre (T = traction, C = compression). Les résultats confirment la validité de l'application de l'analogie du treillis dans la conception. Ils indiquent que les méthodes communément utilisées pour calculer les longueurs d'ancrage des barres droites ou à crochet peuvent être trop conservatives dans le dimensionnement des nœuds et que l'effet de confinement du béton a un effet favorable sur le nœud et autour des barres formant tirant.

ZUSAMMENFASSUNG

In dieser Veröffentlichung werden die Ergebnisse einer Reihe von Versuchen präsentiert, in denen das Verhalten von Knotenbereichen, wie sie in Stabwerkmodellen auftreten, untersucht wurde. Die Versuche umfassten eine Reihe von Trägern mit ausgeklinkten Auflagern und zwei Testserien, in denen die Druck-Zug-Zug und Druck-Druck-Zug Knoten in den ausgeklinkten Trägerenden isoliert betrachtet wurden. Die Ergebnisse bestätigen die Anwendbarkeit von Stabwerkmodellen für Bemessungs- und Konstruktionsaufgaben. Es wurde beobachtet, dass die üblichen Vorgehensweisen für die Bestimmung der Verankerungslänge von geraden Bewehrungsstäben oder solchen mit Endhaken für die Bemessung von Knotenbereichen sehr konservative Ergebnisse liefern, und dass eine Umschnürung des Betons festigkeitssteigernd wirkt.

1. INTRODUCTION

1.1 Background

Mies van der Rohe restated a traditional German proverb in a positive fashion when he said, "The hand of God is in the details". Clearly, the success of any integrated conceptual approach to the proper design of structural concrete must finally succeed or fail according to the degree of assistance it gives the designer in developing adequate and economic details. Marti [1] states "Dimensioning and detailing of D-regions has often been regarded as an inferior task, while in fact, it is of paramount importance for the quality of any reinforced concrete structure." Schlaich [2] urges that dimensioning be carried out initially on the basis of relatively simple models, such as the strut-and-tie model (STM), with a following step of review at "a suitable level of sophistication" to ensure that the details in fact carry out the intent of the dimensioning model. He quite properly points out that even the most sophisticated non-linear finite element analysis (FEA) has important limits when applied to the capacity of details and expecially to describing the behavior of nodes. The authors have felt that the re-emphasis on STM for D regions provides a golden opportunity for introducing rationality of structural concrete detailing. However, in examining the literature, they came to the identical conclusions voiced by MacGregor [3] and Marti [2] who both call for further experimental investigation of nodal zone strength. The authors have been conducting such experimental studies for several years [4,5].

1.2 Objectives

The basic object of this study was to critically examine the application of STM in the detailing of D-regions. Research cannot be carried out to develop empirical design procedures to cover *every* detailing situation. The STM uses a few basic principles to cover a large range of design problems. While the literature contains considerable general information, there is a lack of test data to corroborate assumptions of the strut-and tie model. Working with a specific application to help verify strut-and-tie procedures, a dapped-end beam detail (See Fig. 1) was selected for testing. The STM principles outlined by Schlaich et al. [6] were used to develop details for the discontinuity regions. It became immediately apparent that the existing state of knowledge was particularly troublesome which applied to the nodes. Major attention was then devoted to tests on isolated nodes (Fig. 1b and Fig. 1c).

1.3 Test Series

1.3.1 Dapped Beam Tests

Three different procedures for the design of dapped beam ends were used. Two different STM and two empirically based methods (PCI and Menon/Furlong) were used. A different dapped end detail was tested for each method [4].

1.3.2 Compression-Tension-Tension (CTT Nodes)

To develop an understanding of an isolated CTT-node, a laboratory investigation identified significant behavioral patterns of the CTT-node, and was used to develop design guidelines. The dapped beams served as the prototype for the node tests. Nine node specimens were designed and loaded to duplicate, as closely as possible, boundary conditions that exist at a critical CTT-node in the dapped beams. Variables included concrete strength, lateral confinement provided by transverse reinforcement, anchorage details, and node geometry [4].

1.3.3 Compression-Compression-Tension (CCT Nodes)

The CCT node was also isolated from the end reaction region of the dapped beam. Ten specimens were tested in which concrete strength, size of bearing area, amount of transverse reinforcement, and longitudinal reinforcement configuration were varied [4].

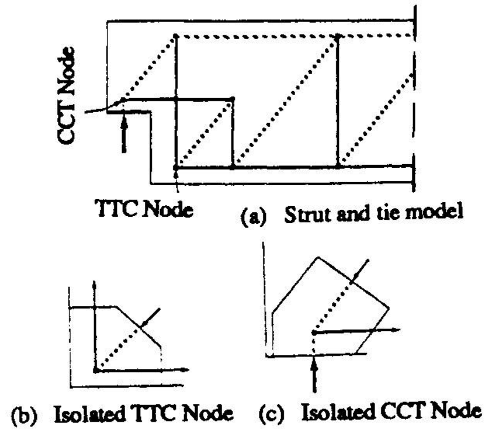


Figure 1 Strut and tie model of the prototype dapped beams.

2. DAPPED END BEAM TESTS

All dapped end details were designed for the same design load levels; a factored ultimate load of 100 kips [4]. The resulting reinforcement layout for the two different STM used, the PCI, and the M/F method designs are shown in Fig. 2. In the actual tests, the dapped end details were provided at the ends of a simply supported beam which was loaded monotonically to failure.

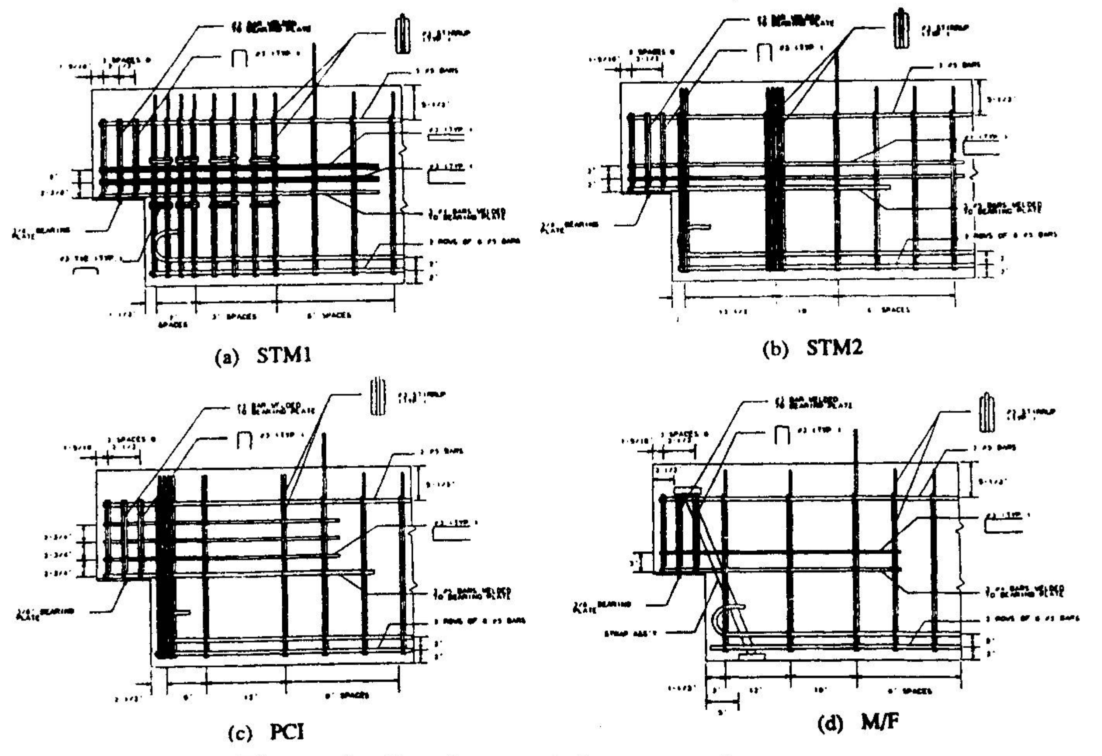


Figure 2. Specimen reinforcement layouts.

The overall behavior of specimens designed using STM was found to be comparable with details designed using current design standards. As shown in Fig. 3 the ultimate capacity of all four specimens substantially exceeded the computed capacity. A ductile failure mode in which the steel yielded before the concrete failed was exhibited by each of the specimens. The STM procedure required slightly more shear reinforcement. The initial cracking load for all specimens ranged from 20 to 30 percent of design ultimate as shown in Fig. 4. In ST-1, cracking was well controlled at service loads. Slightly more cracking was exhibited by ST-2 due to placement of vertical reinforcement farther away from the dap. Initial yielding of reinforcement in both STM specimens was at about 75 percent of design ultimate, substantially earlier than the two empirically designed specimens.

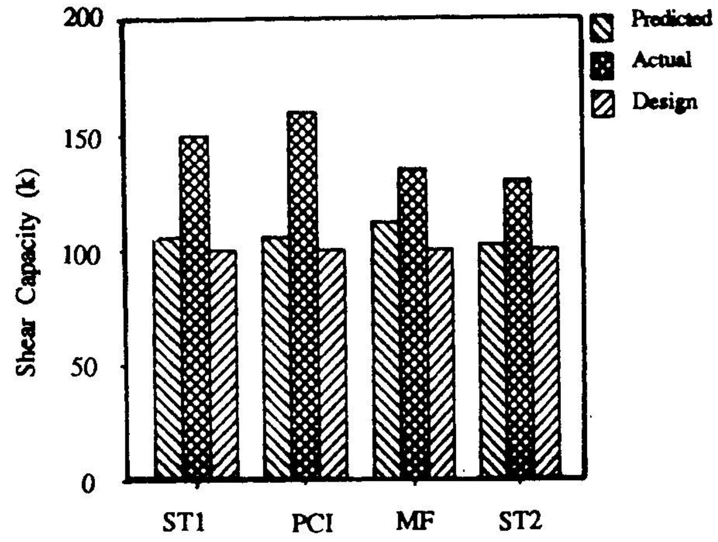


Figure 3 Comparison of specimen shear capacities.

Internal force measurements at the design ultimate load compared well to forces predicted by the design STM. As load was increased beyond the design ultimate load, the distribution of internal forces changed. STM representations of the upper portion of the daps based on measured forces at ultimate were not completely accurate due to the presence of force transfer mechanisms not considered by the STM.

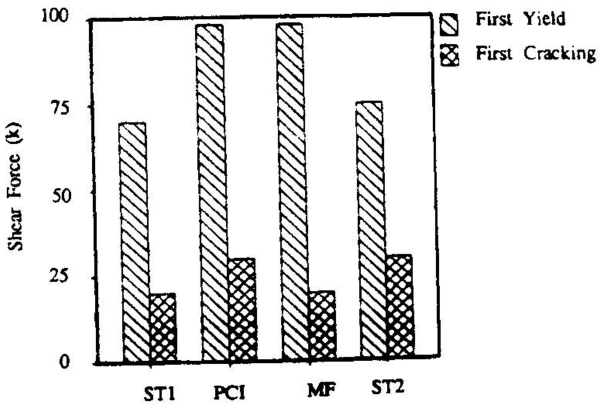
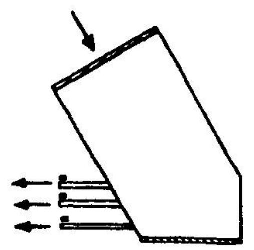
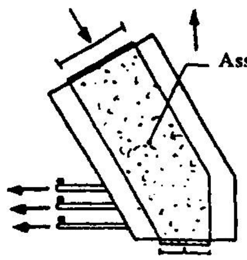


Figure 4 Comparison of cracking and yield loads

Comparison of the behavior of the dapped ends indicates placing the main vertical reinforcement close to the change in section is most efficient. In addition, grouping the reinforcement with as small a spacing as possible appears to offer the best performance. Anchorage requirements based on the STM were found to be conservative and resulted in applied loads well beyond design values. Proper anchorage of the dap horizontal reinforcement and the beam flexural reinforcement was found to be particularly important.



(a) Full Width Loading Plates Used for Mode Specimen A1, B1 and A1-R



(b) Half Width Loading Plates Used for Mode Specimen A2 and B2

Figure 5. General information about the tested CCT-nodes (from Ref. [4]).

3. NODE TESTS

The nodes of the STM represent the locations of change of direction of internal forces, which in the structure occurs over a certain length and width in the node region. The intersecting strut-and-tie forces have to be linked together and balanced in equilibrium in the node region. If one of the struts or ties represents a concentrated stress field (e.g. near a single load, a support or concentrated reinforcement) the deviation of forces tends to be locally concentrated and the node region is relatively small. These kind of nodes are called "singular nodes" and have to be dimensioned with special care. Evaluation of the nodal regions includes checking the nodal boundary stresses and determining reinforcement development requirements for nodes which contain tension ties. Each of these steps requires the determination of the physical boundaries of the node.

3.1 CCT Nodes

The typical critical CCT node in a dapped end beam occurs at the support as shown in Fig. 1(a). This node was isolated as shown in Fig. 1(c). In some presentations of CCT nodes, the tension reinforcement is shown as anchored by use of an external anchor plate. This is seldom found in practice. The usual detail is that straight bars, hooked bars or looped bars are used. Looped bars with confining direct pressure from the bearing plate load are preferred. Sufficient anchorage lengths have to be provided within as well as behind the node. Anchorage lengths can be assumed to begin where the compression struts meet the bars. The effective width of the compression strut can be found by assuming an effective compressive stress in the strut, $\nu_e f_c'$.

The fundamental aspects should allow the designer to determine the geometry of the CCT-node for varying reinforcement distribution and anchorage details (several layers, loops, hooks, etc.). The experimental study by Bouadi [4] provided information about the behavior and transfer of forces within the CCT-node as well as the ultimate strength. Typical test specimens are shown in Fig. 5. Test results with a concrete strength in the range from 2360 to 4680 psi showed crushing of the concrete struts only for the lower concrete strength specimens. In all other cases anchorage failure occurred. The tests indicate the of geometry of CCT nodes shown in Fig. 6. The compressive forces and the tensile force in the reinforcement were increased simultaneously. All specimens experienced post-yield failures including strut crushing, cover splitting, and gross slippage of reinforcement. Statistical examination of the specimens experiencing concrete failure indicated that if $\nu_e = 0.8$ was used, all predictions were conservative with a mean of 1.17 and a standard deviation of 0.14. The CCT node tests indicated:

(1) Specimens were controlled either by anchorage failure or compressive failure;
(2) STM strut orientation angles had been verified as correct in the dapped beam tests. Effective bearing areas based on such orientation gave consistent results for evaluating

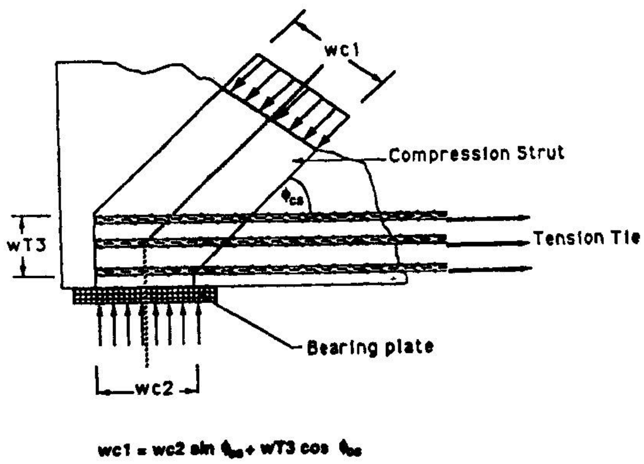


Figure 6. Anchorage detail for CCT-node with directly anchored bars.

tie anchorage and effective compressive strength factors;

(3) The effective compressive stress efficiency factor increased with reduction in bearing area size;

(4) Transverse reinforcement restrained the cracks and increased capacity 35% by preventing anchorage failure;

(5) Anchorage lengths for straight and hooked bars given in the ACI Code were found to be conservative.

3.2 CTT Nodes

The CTT-node is an intersection of a concrete compressive strut and two tensile ties. In steel trusses, bolts, welds, and gusset plates are sized to safely transfer load between the members. In contrast, a CTT-node in a concrete member must rely on anchorage, bond and other internal force transfer mechanisms to transfer strut and tie forces. Anchorage is achieved by providing proper development length or in special circumstances by attaching the reinforcement to bearing plates or other fixed components. The definition of the effective width plays an important factor in the dimensioning process. For the relatively rare case of a CTT-node with anchor plates, the widths of the plates are given as dependent constraints which tend to fix the width of the unknown compression strut. The more practical and generally occurring case is the CTT-node without a bearing plate. For this case the approach of Fig. 7 is proposed.

The efficiency factor for the CTT-node was investigated in an experimental study by Anderson [4]. Figure 8 shows typical test specimens. Other variables included types of anchorages, local confinement and concrete strength. One specimen was subjected to unequal forces in the tension ties in order to induce a different compression strut angle into the specimen. In the tests, general strut failures did not usually occur. The reinforcing anchorage detail was primarily responsible for limiting the ultimate load. However, for design purposes the actual efficiency factor for the concrete compressive strength is of interest. Only one specimen failed by concrete crushing. Using ν_e = 0.8 and taking into account the smaller bearing plate width (4") compared to the compression strut width (6.37"), the experiment/theory-ratio was computed as 1.02.

While data was collected from a relatively small number of CTT tests, the unique nature of the isolated node specimens provides interesting insight into node behavior and design.

(1) Specimens were generally able to reach the design strength which was governed by yielding of tie reinforcement. The ultimate strength of the CTT nodes was affected by concrete strength; however, internal force transfer mechanisms were more affected by the specimen geometry and placement of steel.

(2) In all the specimens, different layers of tie reinforcement were observed to strain at different rates. In the strut and tie model the reinforcement making up a single tie is

normally assumed to be uniformly strained. Major cracks appeared to reduce the available development length for some of the layers of reinforcement closest to the external surface enough to cause a deterioration in the tensile capacity of the tie.

(3) Correlations between the behavior of the node specimens and the prototype dapped beam specimen were quite good.

(4) Evaluation of the strut-and-tie model in the light of the test results indicate that
   (a) cracks were generally parallel with the angle of the compression strut;
   (b) the geometry of the strut is best defined by the strut angle and the width of the outer intersections of the layers of the reinforcement in both directions;
   (c) defining the critical section of the reinforcement by the boundaries of the compression fields appeared to produce reasonable estimates of the capacity of ties anchored through development.

(5) The splitting failures that occurred in several specimens underscored the importance of detailing the CTT-node as a three-dimensional element. Reinforcement should be provided across all planes of weakness to control cracking. Confining reinforcement normal to planes of hooks and bends is especially important.

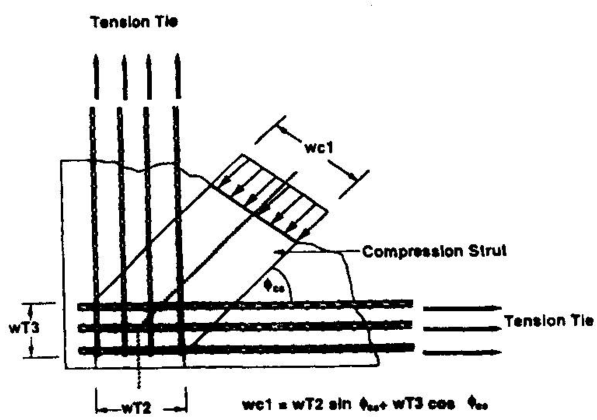


Figure 7 Geometrical approach to define the strut width for CTT-node

4. CONCLUSIONS AND RECOMMENDATIONS

The results of these limited tests show that the STM is useful design procedure for detailing structural concrete. The use of STM along with a knowledge of behavior derived from experimental research seems a good basis for developing efficient design procedures. The STM represents a rational approach which can be extended to detailing situations not covered by existing procedures.

As called for by MacGregor [3] and Marti [1], further experimental verification of other types of details is necessary. In addition, guidelines on analysis and design of nodal regions, serviceability criteria, and tie layout need development. In order to develop comprehensive design criteria for nodes, future studies should include specimens with a number of different bar spacings and amounts of tie reinforcement. Test specimens with high percentages of reinforcement and narrow web widths are also suggested so that effective concrete strength limits could be evaluated more closely. The behavior of specimens with anchor plates and straight or hooked bars needs to be examined. In addition, the effect of strut orientation should be studied more closely. In particular, the effects of skew cracks on the effective concrete strength of the compressive strut should be verified. The isolated node specimens used in this study provide much useful data but admittedly it is never possible to remove a portion of a structural element and isolate it in a manner that does not produce some change in boundary conditions. In spite of that, such node specimens offer a means of acquiring a large amount of data on detailing at a minimal cost.

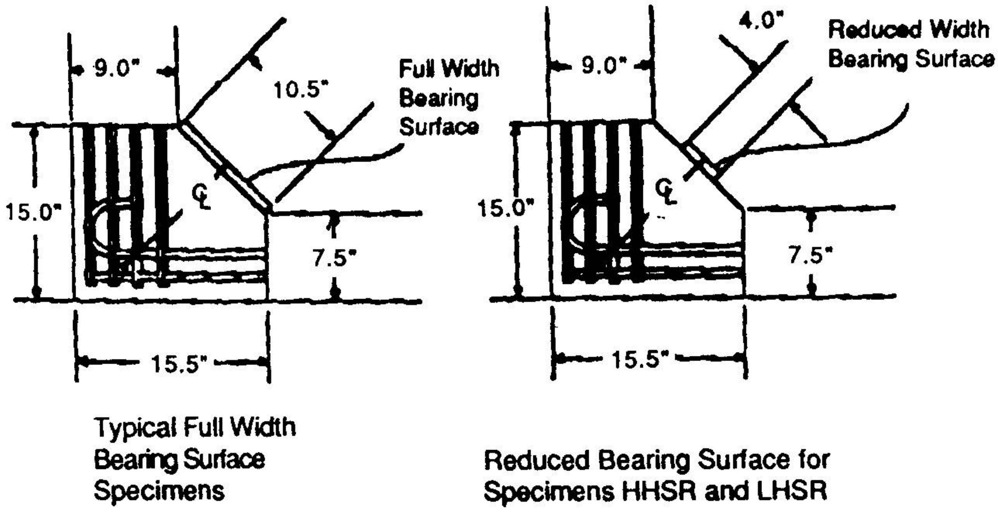


Figure 8 Typical CTT-nodes tested (from Ref. [4]).

5. ACKNOWLEDGEMENTS

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