THE ROAD TO A CODE

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Abstract

Paper summarizes analytical and experimental research leading to revision of AISC structural code for design of pre-tensioned end-plate connection resulting in rationalization of design and economy of material and labour. The interaction between the researcher and designer, and factors involved in the development and acceptance of design code are discussed.

KEYWORDS : Structural Steel Design, Bolted Connections, Finite Element Analysis, Experimental Research, Code Development

1. Introduction.

Serious concern and interest in bolted connections increased in U.S.A. in the sixties, although the connections themselves had been in use for much longer. Precise analysis of bolted connections has always been complicated by their complex geometry, unusual loading conditions, and varying support conditions. The problem became more intractable with the introduction and increasing use of high-strength pre-tensioned bolts.

Figure 1 depicts a type of moment-resisting connection which is particularly efficient for attaching a beam to a column or other support (as "end-plates"), and for attaching two members longitudinally (as "splice plates"). In this paper, both terms are used interchangeably.

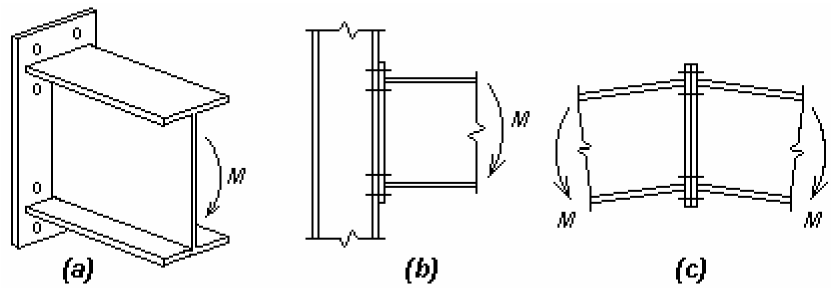


Figure 1. *End-plate Connection : (a) Typical Four-Row; (b) Beam to Column; (c) Frame Member to Frame Member. M = Moment.*

The author and his assistants investigated various aspects of this type of connection for over twelve years. both analytically and experimentally. A major portion of the research was sponsored by the American Institute of Steel Construction (AISC), and the Metal Building Manufacturers Association (MBMA) of U.S.A.

In this paper, the author briefly summarizes the nature, scope and significant findings of the various investigations on bolted end-plate connections conducted or directed by him, and discusses the interactions between technology and personnel involved in the exercise.

2. Background and Literature Review.

The tension region of end-plate connections was conventionally assumed to act as a "tee- hanger" as in Figure 2, in which the applied tension on the tee-stem, corresponding to the tension flange of the beam, is transferred to the support or adjacent component through the bolts on the tee-flange. The web on one side of the beam flange was ignored.

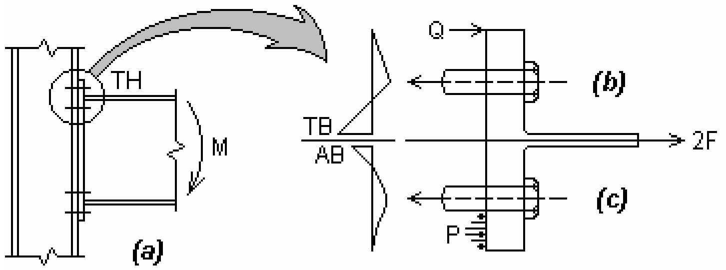


Figure 2. *Tee-hanger Analogy for End-plate : (a) TH - Region Considered as Tee-hanger; M - Moment; (b) Q, TB - Assumed Prying Force and Moment; (c) P, AB - Actual Pressure Bulb and Moment.*

The behaviour of the tee was traditionally analyzed by principles of strength of materials and structural theory, applied to line idealizations. Historical notes on the developments and refinements of analysis of such connections are given in books by McGuire [1], and Fisher and Struik [2], and in Volume SB of the Council on Tall Buildings Monograph [3].

A "prying force" *Q* was postulated by Schutz [4], to satisfy statics under the assumed behaviour. This concentrated reactive force was set to act at or near the edge of the tee-flange (or end-plate), as shown in Figure 2(b). Subsequent investigators (Douty and McGuire [5], Struik and de Back [6], and Nair et al [7], proposed various prying force formulas. The formulas developed by Nair et al were included in the 7th edition of the American Institute of Steel Construction (AISC) Manual [8].

Agerskov [9], introduced refinements for the bolt head effects and shear interaction. Many took the limit state approach with various collapse mechanisms : Surtees and Mann [10], Zoetemeijer [11], Grundy et al [12], Packer and Morris [13], Granstrom [14], Mann and Morris [15]. Most of these analytical investigations were backed by tests, and the formulas and the analysis procedures were adjusted by findings from the tests. Sherbourne [16], and Bailey [17] also conducted extensive testing.

The author's initial interest in the area, in the late sixties, was mainly on the finite element (F.E.) modeling of bolted connections [18,19]. Bose et al [20], and Nair et al [7] also reported contemporary work in that area.

By the early seventies, the need for more and better information on the behavior of "typical" end-plate connections with four rows of bolts as in Figure 1(a), became quite critical. In response, the AISC and MBMA initiated an extensive research project with the author as principal investigator. The project grew to encompass wide ranging F.E. studies, experimental investigations, and yield line theory applications.

As part of this and other unfunded research, the author and his assistants extended his finite element application methodology specifically to the end-plate connection, and analyzed hundreds of connections and their components by the F.E. method. They also carried out numerous tests on full and half-size steel connections and on photo-elastic models.

Initially the author came up with a stiffness approach to design, based on the moment-rotation relationship, [21]. But the AISC/MBMA research committee favoured the strength approach based on maximum plate stress, and the bulk of subsequent research and evaluation focussed on this.

Many papers and discussions have been published on these investigations by the author and his associates. References [18, 19, 21 to 31] cover typical and significant activities and findings. Nineteen topical reports were submitted to the research sponsors. Sixteen master's degree theses and one Ph.D. dissertation resulted from the total research effort.

Based on the findings from the research, the procedure proposed by the author [24], for the design of typical end-plate connections was incorporated into the 8th edition of the AISC Manual [32].

Meanwhile, other researchers also reported parallel work in the area, including Lipson and Haque [33], and Ioannides and Tarpy [34].

Even after the acceptance and publication of the revised design method, finite element work on end-plate and other bolted connections continues to be reported, affirming the practical importance of the topic. At the same time, not only the method based on the author's research, but subsequent extensions thereof to multiple bolt row connections, still remain very much part of the AISC code.

The preceding review does not presume to be comprehensive. Considerable valuable work on connections has been going on and is being carried out in many parts of the world. Only the material that provided the background and frame of reference for the author's efforts has been mentioned.

3. Methodology of Investigation.

The large number of research tasks of a similar nature both necessitated and enabled the evolution of a formal methodology to develop usable results and procedures from the F.E. analysis, which may be summarized as follows :

(1) Selection of pertinent variables;

(2) Determination of their practical ranges;

(3) F.E. sensitivity studies to order variables according to significance and choose dominant ones;

(4) F.E. convergence studies to determine the optimum mesh combining precision and economy;

(5) F.E. correlation studies on two-dimensional (2D), three-dimensional (3D), and combination models, to determine factors that would enable the prediction of 3D values from 2D results;

(6) Calibration tests on a few prototype specimens or models to check and modify the F.E. models;

(7) F.E. parameter studies on statistically valid combinations of parameters, non-dimensionalized for general applicability;

(8) Development of prediction equations from the F.E. results, by means of similitude principles, and regression analysis programs;

(9) Simplification of equations to reflect practical parameters as far as possible, and incorporation into a formal analysis or design procedure; and,

(10) Validation tests on full-scale specimens to check and confirm the proposed equations and procedures.

4. Finite Element Analyses.

4.1. Analyses conducted.

After sensitivity and convergence studies, the mesh schematically shown in Figure 3(a) was chosen for the 2D plane stress analysis. The moment loading on the beam was applied as the equivalent nodal loads corresponding to the bending stress distribution shown in Figure 3(b).

To permit the independent extension of the pre-tensioned bolt and the compression of the end-plate under the bolt head (or nut), two separate meshes were provided overlapping each other in the same plane, and connected with common nodes at the line of contact between the underside of the bolt head (or nut) and the plate outer surface, as depicted in Figure 3 (c,d).

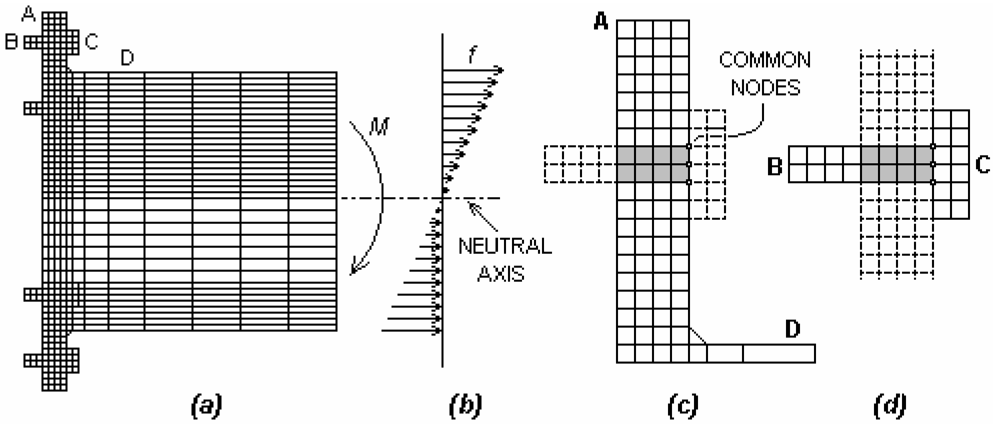


Figure 3. *Discretization for 2D Analysis : (a) Mesh scheme, M = Moment; (b) Bending stress as load on beam end, f = Mc/I; (c) Mesh detail in end-plate projection; (d) Mesh detail in bolt head (or nut) and shank. Shaded areas in (c) and (d) demarcate the overlapping mesh region.*

The 3D mesh was very similar in the longitudinal section, and had additional mesh divisions in the transverse direction parallel to the plane of the end-plate. Because of the disproportionately higher time and core needs for 3D analyses, the number of 3D elements was much lower than for 2D.

Table 1 lists significant details of the various F.E. studies conducted on different end-plate (and related) connection configurations, as part of the author's research. Most of the research work has been reported and findings have been summarized in the publications listed.

Table 1. *Finite Element Analyses Conducted*

Student Name, (University), Year	*Connec -tion Type*	*No. of Connec -tions*	*No. of Nodes*	*No. of Ele- ments*	*2D or 3D*	*Program used*	*Purpose*
Battles (A)1972	TSA	15	263	206	2D	WILMOD	Parameter study
Graddy (A)1973	TSP	2	559	488	2D	WILMOD	Feasibility study
	TSP	2	572	287	3D	LEVMOD	
[Author and Graddy (A)1974]	TSP	13	559-581	488-508	2D	WILMOD	2D/3D correlation study and test check
	TSP	13	572	287	3D	LEVMOD	
Huang (A)1974	TSP	15	581	508	2D	WILMOD	Sensitivity study
Jeffrey (A)1974	TSP	83	581	508	2D	WILMOD	Parameter study
Chaudhari (A)1975	MSP	46	544	452	2D	WILMOD	Parameter study
	FSP	46	444	376	2D	WILMOD	
Avery (A)1976	TSP	45	581	508	2D	WILMOD	Parameter study and test check
	TSP	8	572	287	3D	LEVMOD	
Oswalt (V)1978	SPP	15	73	51	2D	FEABOC-1	Bolt head and weld effects study
Saxena (V)1978	UTH	18	276	228	2D	FEABOC-I	Photo-elastic test check

TSA : Top angle of top and seat angle connection
MSP : Multiple bolt row splice-plate
SPP : Splice-plate projection
(A) : Auburn University
TSP : Typical splice-plate with four bolt rows
FSP : Flush splice-plate, multiple bolt rows
UTH : Unstiffened tee-hanger
(V) : Vanderbilt University

Student theses are cited in the Table, together with the University and year of graduation, to give them due credit. Further, some of the work, as by Chaudhari and Saxena, has not been published; in such cases, and even in other cases where additional information is required, their theses which are in public domain, may be used for reference.

4.2. Problems and solutions.

Bolted connections pose special problems for analysis by structural theory or continuum mechanics. The following are the major complications requiring innovative solutions :

(a)Thickness effects :

The thickness of the bending segments of the connected plate elements is of the same order of magnitude as the bending spans. This caused the following complications :

(i) The plate at the connection behaved as a deep beam or continuum, rather than as a simple beam in bending as assumed generally.

(ii) The pre-tensioning of the bolt compresses the plate region under and around the bolt head (or nut), and tends to curl the plate outward at its free edge, much as a pillow would when pressed down at the centre, as depicted in Figure 4.

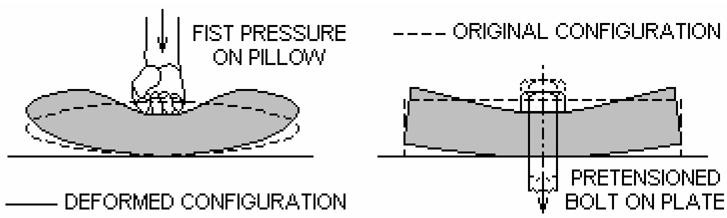


Figure 4. *Pillowing Effect of Pre-tensioned Bolt on Plate.*

(iii) The reaction at the back of the end-plate is in the nature of pressure bulbs rather than concentrated forces as assumed by earlier researchers. See Figure 2(b) and 2(c).

These thickness effects of short bending spans, deep beam action, and the pre-tension “pillowing” were all accounted for by the use of plane stress idealization (parallel to the tee-hanger or end-plate cross-section) or solid elements, in preference to plate bending elements in the plane of the tee-flange or end-plate.

(b) Simulation of bolt pre-tension and varying support conditions :

As the plate deforms under the actions imposed on it by the bolt pre-tensioning and the external loading, the support regions at the back of the plate segments vary in location and extent with the nature and magnitude of the pre-tensioning and loading processes.

This situation was handled by specific manipulation and careful application of available F.E. algorithms and by development of special techniques, routines, and programs.

Bolt pre-tensioning was simulated in two stages, as follows :

(i) Application of the specified pre-tension force to the bolt end nodes with no other external loads, to reflect the bolt tightening operation; and,

(ii) Imposition of the resulting bolt elongations as prescribed displacements at the bolt end nodes for the subsequent external load analyses, just as if the tightened nut was left free to interact with the subsequent external loading.

As already mentioned, in the 2D plane stress analysis, it was required to represent the bolt and the plate through which it passed as two separate entities connected only at the bolt head (or nut) and plate interface, by means of discretization of the two regions with separate nodes and elements in the same plane, as indicated in Figure 3(c,d).

In both the 2D and 3D analyses, hexagonal bolt shanks and heads (or nuts) were modeled with square or rectangular cross-section. Limited studies indicated that this was of no great consequence.

The variable support (or "rolling contact") problem of determination of the final deformed profile for any particular loading was solved iteratively. To start with, the entire back of the tee-flange or end-plate was assumed to be in contact with the support. Under any particular load, for any cycle, if the reaction at a support node was tensile (i.e. pulling away), the node was released to move freely in the next cycle. If a previously released node migrated back into the support region, the node was re-supported for the next cycle.

The procedure was repeated until no change occurred in the support conditions.

(c) 3D versus 2D analyses :

Complete 3D analysis of the connection, in the numbers needed for a parameter study, would have (at that time) involved inordinately heavy expense, time, and effort. On the other hand, a 2D plane stress analysis alone would have been too crude and unrealistic a model from which to draw reliable conclusions.

To address this dilemma, a 2D/3D correlation study was conducted [23], from which magnification factors were determined to predict the more realistic 3D rotations and stresses from the more economical 2D results.

(d) Inelastic behaviour :

Most of the analysis and evaluation were restricted to the elastic stage because at that time only working stress design was required.

Subsequently, bilinear material analysis capability, with an effective strain yield criterion and a secant modulus flow rule, was introduced in the 2D analysis. In a separate project, the effects of various other failure theories on the F.E. modeling were investigated, but the differences were slight.

(e) Massive data, processing, and output :

To generate the massive input data in a speedy and error-free manner, pre-processors were written. To avoid unnecessary repetitions of expensive calculations such as sub-parametric element stiffness and nodal stress matrices, and to enable continuation of the analysis over many runs, elaborate storage and retrieval schemes for input and generated information were developed. Post-processing capabilities were added to digest and efficiently display the voluminous output.

During the initial stages of the project, these and other special features were built into available F.E. programs. In particular, the 2D program by Wilson [35], was enhanced into "WILMOD", and the 3D program by Levy [36], was further developed into “LEVMOD".

Subsequently, the author developed a completely new program “FEABOC”, acronym for “*F*inite *E*lement *A*nalysis of *BO*lted *C*onnections”, with all the information flow and processing being aimed at efficient data generation and automatic iterative solution for the specific analysis of pre-tensioned bolted connections, and with built-in pre- and post-processors, [31]. The latest version (1983) could even handle separation of one bolted plate element from another flexible adjacent component.

5. Physical Tests.

As outlined in the methodology section, physical tests were used

(1) to check and refine the F.E. models, and,

(2) to validate the proposed procedures.

The end-plates were tested as mid-span splices in a simply supported beam under two-point loading, transferred from a central load via a load transfer beam, to develop only moment at the connection, as in Figure 5. In a separate study, it was shown that for practical beams, the contribution of shear was negligible.

It may be noted that the beam tension flange, critical to the end-plate design, was now at the bottom, and not at the top as in Figure 1 for normal end plates. The tension flange area of the end-plate was extensively strain gaged on both symmetric sides and averages taken.

5.1. Tests conducted.

Tests on end-plates and associated components carried out are listed in Table 2, again with student theses listed as references. While the details of many of the tests have not been published In journals, the validation tests and the testing procedures have been published, [26,28].

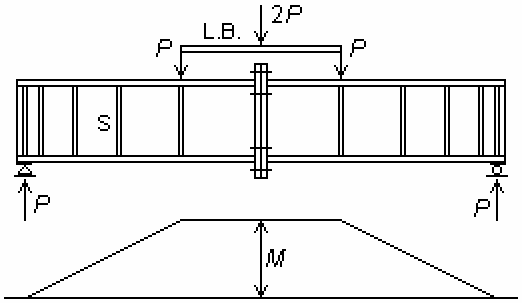


Figure 5. *Test Set-up and Bending Moment Diagram.*
L.B. - Load Transfer Beam
S - Stiffener
2P - Applied Load
M - Bending Moment at Connection, = P.a

Again, the unpublished work of Daniel, Saxena, Byers, and Beall, as well as more details of the published work of other students, will be available from the theses listed in the Table.

Table 2. *Connection Tests Conducted*

Student Name, (University), Year	*Connection Type*	*No. of Connections Tested*	*Material*	*Scale*
Daniel (A)1975	TSP	8	MS	Full, half
Avery (A)1976	TSP	7	MS	Full
Saxena (V)1978	UTH	18	PE	Small model
Byers (V)1979	TSP	10	MS	Full
Beall (V)1980	TSP	10	MS	Full

MS : Mild steel; PE: Photo-elastic epoxy. (For other notation. see Table 1)

5.2. Problems and solutions.

(a) Lateral buckling :

The testing involved many complications in specimen design and fabrication, test set-up and data logging. In particular, lateral twisting and consequent premature failure became the bane of the tests on beams with splice-plate connection specimens.

Initially, simple wooden struts from the load frame side columns to the test beam flanges were used, but they turned out to be too much trouble, and relatively ineffective. After many trials, an effective lateral bracing system was developed, consisting of stiff wooden frames with side rollers running on the test frame column webs as in Figure 6, permitting large vertical deflections, enabling the beams to develop their ultimate bending capacities, [28].

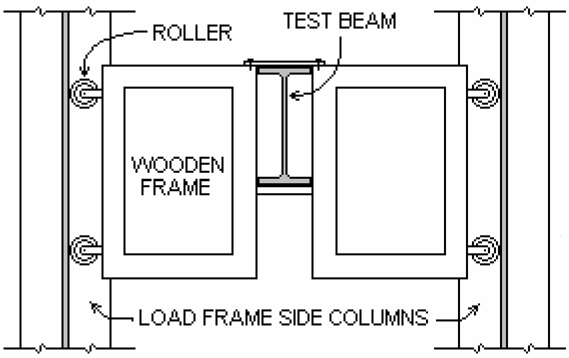


Figure 6. *Wooden Frame on Rollers for Lateral Bracing of Test Specimens.*

(b) Connection rotation :

The second major complication was the measurement of the nominal angle θ of connection rotation.

Researchers had used various techniques to measure the rotation directly, including a light beam reflected off of a mirror attached to the top of the end-plate.

But a more common and simpler method was to measure the separation δ of the end plates between the top two rows of bolts, from which the rotation could be computed as (δ/d), *d* being the beam depth.

The author first used dial gages carried on a metal frame attached to (and hence "floating" with) the connection, to measure the plate separation at the bottom flange.

Later he developed a simple and elegant device with a strain gage stuck on the circular spring plate of a caliper and calibrating it for end separation, as in Figure 7, [28].

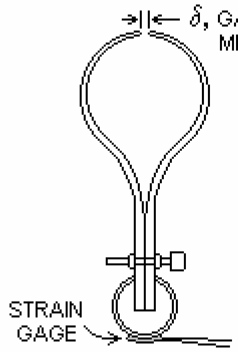


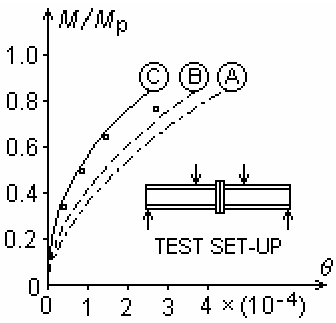
Figure 7. *Calipers Strain Gaged, to Measure Plate Separation.*

(c) Lack of correlation between analyses and tests :

The results from the first F.E. discretization consistently showed computer models to be much more flexible than their physical counterparts.

Upon further detailed analyses of connections with and without bolt heads (or nuts) and fillet welds, it was discovered that the bolt heads (or nuts) and fillet welds, normally considered "minor details" in F.E. models, contributed significantly to the connection stiffness.

Figure 8. *Effect of Bolt Head / Nut and Weld on Connection Stiffness.*
Mp = Plastic Moment
▫ = Test Result
Finite Element Results :
A = Without Bolt or Weld
B = With Bolt, without Weld
C = With Bolt and Weld



This omission was promptly rectified to give the more realistic model of Figure 3, and the enhanced model was used for the parameter studies. A separate investigation [29], quantified their influence.

Figure 8 is one of the more dramatic cases of improvement of agreement between computed and measured results, after inclusion of bolt head (or nut) and fillet weld in the finite element model.

5.3. Photo-elastic Tests.

Contrary to what had been postulated or accepted by most earlier investigators about the prying force, the author's F.E. analyses had showed from the very beginning that prying action was very slow in developing, and very mild in its adverse effects even when fully developed, in connections with pre-tensioned bolts.

While experimental evidence of increase in bolt forces had no doubt been offered as proof of the existence and magnitude or prying forces, no reports were available of any actual measurement of the actual location or magnitude of the prying force itself, let alone the stress distribution inside the plate.

Hence the photo-elastic project was undertaken with the sole objective of examining the elusive prying force. A special calibrated metal bolt and an external spring device was used to simulate the bolt pre-tension, as shown in Figure 9.

The photo-elastic test results confirmed the F.E. predictions. The only disappointment was that the maximum prying stresses in the specimens could not be quantified because they were too small to be visible as fringes!

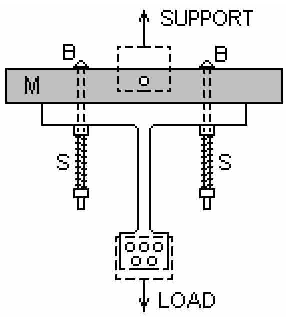


Figure 9. *Photo-elastic Test Specimen Set-up.*
M - Rigid Metal Base
B - Metal Bolt
S - Calibrated Spring

6. Code Implementation.

6.1. Design procedure.

The methodology outlined led eventually to the development of a new method for the design of the typical four-row end-plate connection of Figure 1(a), and its inclusion in the 8th edition of the AISC Manual [32].

The results from the F.E. analysis of hundreds of end-plate connections, corrected for bolt head (or nut) and fillet weld effects and modified by the 3D/2D correlation factors, were fed into the regression analysis program SPSS, [37].

The results generated from the numerous F.E. analyses of entire end-plate connections were first evaluated to statistically generate a prediction equation for connection stiffness by way of moment-rotation relationships as a function of component dimensions, bolt locations, material properties, and applied moment, [21]. It was suggested that an engineer could design a connection for any desired stiffness, with 95% being recommended for a “rigid” connection.

However, the sponsors having decided to pursue the strength route, the same data was re-evaluated to develop the maximum stress as a function of the other variables. The terms of the resulting governing equation for connection capacity were manipulated in various ways until a practically meaningful and statistically strong relationship resulted.

The outcome was a "moment modification factor" that could be applied to the classical double cantilever method, [24]. Hence the proposed procedure has been called the "modified split-tee method". This method resulted in plate thicknesses averaging about a third less than by the prying force method.

6.2. Validation.

The recommended designs were satisfactorily validated for typical end-plate connections by confirmation tests.

The committee wanted the author to compare the designs of all the available sections from the two sponsors, 192 from AISC and 44 from MBMA, by the proposed method, with the current AISC/MBMA method, and one other method contemporaneously proposed by Agerskov [9,38].

Figure 10 depicts the comparison of the three sets of designs. The designs nicely fall into three bands shown shaded in the figure, with AISC/MBMA giving the thickest plates and the author’s the thinnest, [39].

It is also clear from the shapes of the bands that Agerskov’s revision was basically the same as the current AISC/MBMA prying force method with a reduction factor, but the author’s was conceptually different. Further in the proposed method, the scatter was least and the variation smoother.

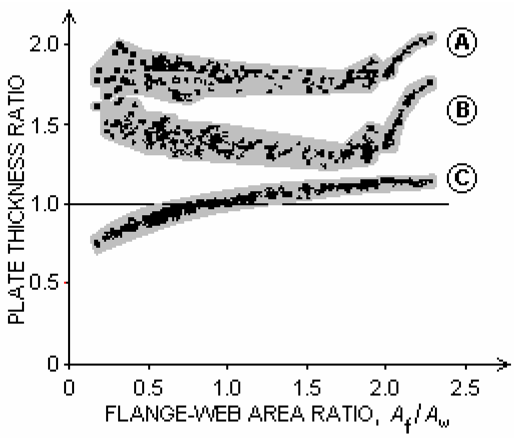


Figure 10. *Comparison of End-plateDesigns by AISC/MBMA, Agerskov, and Auhor's Methods.*

A - AISC/MBMA METHOD
B - AGERSKOV METHOD
C - AUTHOR'S METHOD

Then a question arose as to how thin the plate could get before the connection became critical. To answer this, a project was undertaken (Beall, 1980) to test plates whose thicknesses were progressively reduced from the new design requirement in two stages, with the bolts as required by the new design, as well as one size smaller. Although thinner plates led to greater deflections, premature failure as such resulted only with the thinnest plate and smaller bolt combination.

6.3. Argument and rebuttal.

The proposed procedure raised a lot of heat and dust. It had been based mostly on computer-based parameter studies and statistically evaluated results. The resulting plate thicknesses were disturbingly thinner than by the current procedures. Most of all, it completely did away with the familiar and comforting prying force.

The research sponsors were therefore extra careful to air the proposal procedure widely and well before recommending its inclusion into the code. An exciting exchange resulted [40], with the author having to answer each point and convince every discusser [26].

The discussion [40], to the author’s original paper [24], represents only part of the reaction to the proposed procedure. There were quite a few telephone calls and letters vehemently contradicting the author’s conclusions and opposing the new proposals. One constant refrain was that statics would not be satisfied without the prying force, and to this and other arguments, the author had to provide satisfactory clarifications and counter explanations, [26].

In particular, there was one end-plate which Agerskov [38], had predicted was too thin to develop the capacity of a certain beam according to the proposed method. The sponsors wanted the author to settle the argument by a prototype test. To the author's (and the sponsors’!) relief, the test demonstrated the adequacy of the proposed method for that particular connection also [39].

Finally, the committee recommended the procedure to the top echelon of AISC, which in due course approved the recommendation. The author was asked to provide charts and tables for selection of end-plates to develop the moment capacity of various standard beams, for inclusion into the next edition of the AISC Manual.

7. The Human Face of Engineering Research.

A main motivation of this paper was to bring out various aspects of the human angle of the research reported herein, shared possibly by all engineering research. By definition, engineering research has to be application oriented, and must result in some service or product for use by mankind. It is precisely this which involves human factors affecting the course and outcome of the research. In particular, the author would highlight the following aspects of the human-technology interaction :

7.1. Involve the practitioners.

The end user of the research is the designer and the fabricator. Involving them in the early stages of research is often a potential problem area for the academic researcher : The field engineers apparently do not appreciate the “high-tech” nature of research, the intellectual capabilities involved in the planning and execution of the research, the need for mathematical rigour, etc. etc.

Soon however, the researcher realizes the depth of understanding of the true behaviour of actual structures and components which the practitioner brings to the team, and appreciates the warning signs that the practitioner sees but the researcher misses regarding the direction in which the research is heading, and so on.

The author learnt a lot from the practising engineers on his committee. He would cite one instance when his committee chairman took one look at one of the specimens scheduled for test the next day, pointed to a particular weld, and said that the connection would fail right there before the beam reached its capacity – which it promptly did.

The specimen was part of the author’s academic exercise in fractional design of experiments, and unfortunately had not been analyzed by finite elements. The premature failure meant waste of the specimen from the point of view of valid points for regression analysis.

Thereafter, he checked all subsequent specimens by computer analysis, and as insurance, cleared them with the committee.

7.2. Resistance to change.

Research is usually initiated to explore into the unknown, and more often than not, the new investigation comes out with the unexpected. Sometimes however, the fresh discovery flies in the face of “common sense” and long tradition, and then the fur begins to fly.

Simply by suggesting finite element analysis as an analysis tool at a time when it was just finding exotic applications, the author had rushed in where angels would have feared to tread. Luckily for him, the prying force method had been milked for all it was worth by then, and the prospect of many more tests must have been dismaying to the sponsors. His proposal had at least the edge of novelty. He also had the advantages of ignorance, because being the new kid on the block, he had not been “brain-washed” with current practice in the field.

So, when the author found that the current favourite prying force theory was not borne out for pre-tensioned bolts, he was not terribly shocked. But most of the others had a hard time reconciling not only to the methodology but to its outcome as well.

While most fabricators liked the resulting economy of the proposed design, many academics and designers, including some giants in the steel connection field, were (perhaps rightly) concerned about the absence of prying force criterion. The ensuing battle has already been described.

In the final analysis however, it was exactly this final exercise that convinced the detractors, and confirmed – and helped refine – the design method. It was an educational and humbling experience too for the author. The moral is that a design code should not overlook basic differences of opinion from experts, but must reconcile differing views to everyone’s satisfaction.

7.3. Divergent hopes

In such broad-based research of great practical import as reported, chances of greatly differing perceptions and expectations are high. In this case, the critical parameters were different for the two sponsoring groups. While the assembly line pre-fabrication focus of MBMA forced them to concentrate almost exclusively on strength with minimum material, AISC was equally concerned with stiffness.

However, the fact that the proposed design procedure resulted in considerable savings of material and labour in the end-plate connection, with adequate stiffness for most practical situations, resulted in the goals of the two groups converging sufficiently closely to permit a common acceptable code.

7.4. Simplify, simplify

The author still remembers the time he presented to the sponsors at great length and in high style, his long and mathematically impressive first design equation, in all its finery of three-decimal exponents on about ten parameters, guaranteed 98% statistically valid, the result of weeks of hard labour. All sat frozen till the finish, and after a decent interval, the committee chairman, obviously voicing the feelings of all the practitioners on his committee and elsewhere, chuckled and said : “*Fine, Krishna. Now give us one we can actually use!*”

The chairman’s point was simple : The formula was intended for the designer and fabricator for working out on the back of an envelope, not for the professor or graduate student with a computer or programmable calculator. So the formula had to be simple, and it had to fit familiar patterns ingrained over decades of successful use. In short it had to look like $f = Mc / I$, or else it wouldn’t fly.

Which the author made it look, after picking up the pieces of his broken heart, and quenching the fires of bottled up anger. With some more weeks of near futile effort and with a healthy dose of luck, he came up with a new combination of terms which could make practical sense to one and all. It was only a slight modification of existing procedures, except that the modification would build in the wisdom distilled from the eight years of research, and harvest the economy resulting therefrom.

7.5. Watch out for the nail!

As many researchers would have discovered, it is often the “insignificant” detail that can make or break the result of tedious research, like a war being lost for lack of a nail. The author has already mentioned the havoc created by the initial omission of the humble bolt head/nut and the fillet weld.

Even more dramatic was an accidental omission in the one validating test that would have convinced the committee that all those years of research didn't come to naught by the legitimate query of one man from across the seas whose design was different. Most of the committee was present at this proving test, along with a few other admirers (and doubters!). The specimen had been fabricated exactly as per the proposed design. The test started in fine style, and the specimen started struggling at about a quarter of the estimated collapse load.

The author promptly packed off the committee to lunch while he and his new graduate student went over the test set-up inch by inch and item by item. Almost by chance, the author discovered the lateral bracing had not been correctly constrained; the freshman to research had assumed it was just a useless appendage which only hid the real action from curious eyes, and had not tightened the nuts.

Deleting the expletives that were amply called for, the author simply thanked his stars and inserted the lateral bracing and went on with the test when the committee returned from lunch. The specimen took 10% more than the estimated load before it gave up.

8. Conclusion.

The principal findings from the research into end-plate connection behaviour, leading to the development of the new design procedure, were as follows :

(1) Prying force is not a significant factor in end-plate failure, because the pre-tensioning eliminates or postpones the development of the reactive force, and hence may be omitted from design considerations in most cases.

(2) Tee-hanger analogy is also not quite applicable to end-plate connections, because of the lack of their symmetry with respect to the beam tension flange. The forces in the bolt rows on the two sides of the flange are unequal under service loads.

(3) The beam proportions influence the end-plate behavior; in particular, the ratio of the beam tension flange area to the beam web area (A_f/A_w) is a significant parameter. (See Figure 10.)

(4) The plates designed by the new procedure are 30 to 40 percent thinner than the earlier design. They are quite adequate to develop the attached beam capacity. However, where connection deformation could be critical, thicker plates and/or stiffening of the adjacent components may be necessary.

The most satisfying outcome of the research was that the same methodology as used by the author for the standard four bolt row connection, and initially the same program FEABOC, were used for extending the research into the next phase, namely the behaviour of splice-plate connections with more than two rows of bolts at the beam tension flange, as in Figure 11.

The author and his Ph.D. student Radha Krishna (Ph.D. dissertation, Vanderbilt University, 1981) tested only five specimens, all of 914 mm beam depth, but they analyzed many more cases by the F.E. and yield-line methods.

In 1981, the author handed over further research to Professor Thomas Murray and his assistant Kukreti of the University of Oklahoma. In due course Murray's team came up with a design procedure for multiple bolt row connections, and it too was adopted by AISC.

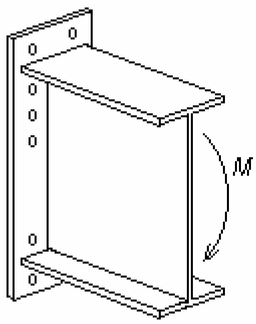


Figure 11. *Multiple Tension Bolt Row End-plate Connection. M = Moment.*

One road ends; another begins.

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