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Forensic Engineering Structural Failure Review By Finite Element Analysis

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Background and Problem

A Florida Engineer was charged by the Florida Board of Professional Engineers with incompetence and negligence because of his design, and his fabrication of the metal roof trusses for a hanger/home in Florida. The engineer personally designed, supervised fabrication, and specified the field modifications required due to conflicts of the bearing height, and truss damage during shipment of the trusses to the jobsite. A complaint was filed by the homeowner and investigated by the board's consulting engineer.

The consultant investigated and alleged that the modified heel connection on the house truss was grossly inadequate to transfer the code mandated loads for this home. No failure has occurred since the home has not been subjected to full code mandated wind loads. The following analysis follows the investigation, and formal hearing before an administrative law judge in Florida.

An after the fact, finite element analysis was performed by W. Bracken to verify the consultants allegations. This analysis by Bracken was performed after the conclusion of the case against the engineer of record.

Design, Fabrication & Erection

This review will analyze the as-built and revised capability of simple light gage metal trusses used in an airplane hanger/house in Central Florida. The trusses were designed, fabricated, and modified by a registered Florida engineer. The heel connections were fabricated with five #10 TEK screws (smaller) rather than fourteen #12 TEK screws originally specified by the engineer of record for the heel connection. The fourteen #12 TEK screws were shown on the permit drawings signed and sealed by the design/fabrication engineer of record.

The engineer of record was charged with, incompetence and negligence, and prosecuted by the Florida Engineers Management Corporation, the investigative/prosecution agency for registered professional engineers in Florida. The design engineer of record, emphatically asserted that the screws used were #12

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TEK screws since the smaller #10 TEK screws were to difficult for the erection personnel to handle. The investigation, using a comparison of the job screws to #10 & #12 TEK screws, confirmed that all screws installed in the trusses were the smaller #10 TEK screws. The #10 screws had 70% of the shear strength of the #12 screws that the engineer of record thought he had used. All joints used 5 TEK screws rather than the 14 TEK screws shown at the heel connection on the 'shop drawings' provided by the engineer of record.

The engineer of record's defense was that his original design was over-designed and actually required fewer screws than he had originally calculated. He insisted that #12 TEK screws were used in the fabrication. He testified that the later version of his personally written computer program, required five screws rather that the 14 specified using his initial computer program. The five screws that were installed in lieu of the 14 screws originally specified in each heel connection member, provided "plenty of connection" in his opinion. He wrote his own computer program, (spread sheet) to perform the finite element analysis of the truss joints. No peer review of his computer analysis was performed or presented to verify his calculations. When the truss was analyzed using standard engineering calculations, the design engineer of record connections provided only 26% of the required shear transfer at the heel connection. He stated *"the heel connection no longer has shear, but rather only simple rotation!"* He even presented a small wooden pin connected truss model to demonstrate his theory to the judge. He testified that shear transfer between the top chord and the bottom chord at the heel is no longer present, in his "new" theory confirmed by finite element analysis. See Figure 1 for the loads on the different members of this truss. He stated that the *"loads are distributed to the other*

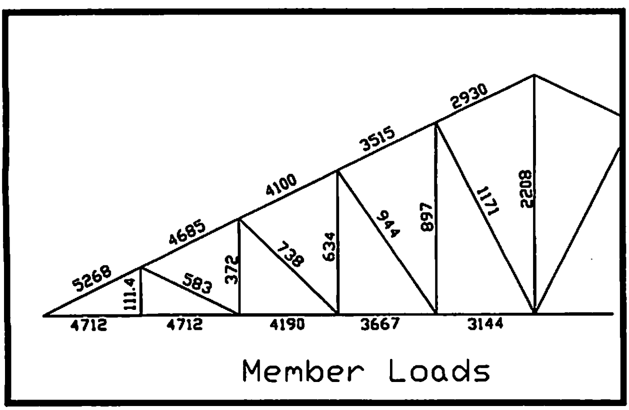


Figure 1
Member loads on one half of his symmetrical truss.
By inspection the heel connection was the most heavily loaded.

members and joints in the truss, therefore the heel is not a critical joint as previously thought by engineers". He stated that he had used a finite element analysis to confirm his design assumptions. Since the Board's expert used old fashioned hand calculations to analyze the critical heel connection, and had not analyzed each connection in the entire truss. *"The board engineer's calculations failed to show the complete picture of the stress transfer to the other parts of the truss"*, stated the design engineer of record during the hearing.

Another interesting point was the design was certified to meet 120 MPH rather than the 100 MPH required by the Standard Building Code in that specific area. This analysis used a 100 MPH wind load because the code only required 100 MPH. The deficit between 100 MPH and 120 MPH would be considered a contract dispute and therefore was not a factor that the Florida Board of Engineers would discipline.

Field Problems during installation

During the erection process it was discovered that one end of the common hanger/house truss bearing wall was 18 inches higher than anticipated during the fabrication of the trusses. The end condition was field modified by cutting 8 inches (See Figure 2 & 3) off the heel connection. A new upset truss bearing surface was field created to allow the truss bottom chord to remain horizontal and still bear on the common wall between the hanger and residential portion of the structure. This created a problem at the valley between the house and hanger, since the house roof slope no longer formed a valley between the hanger and the house. This was solved with the top chord member added above

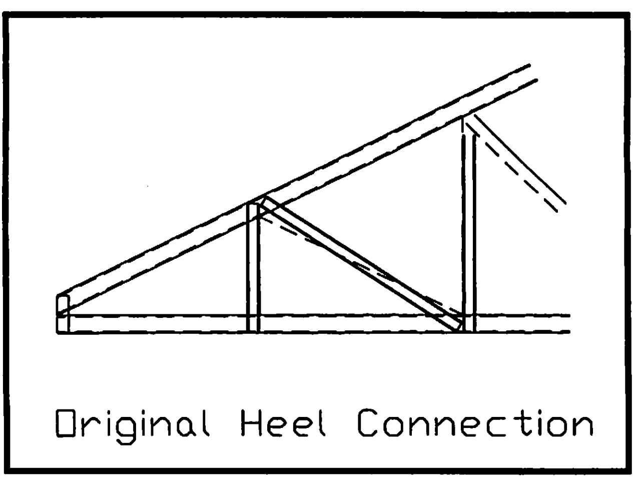


Figure 2
This was the original heel connection configuration before field modification.

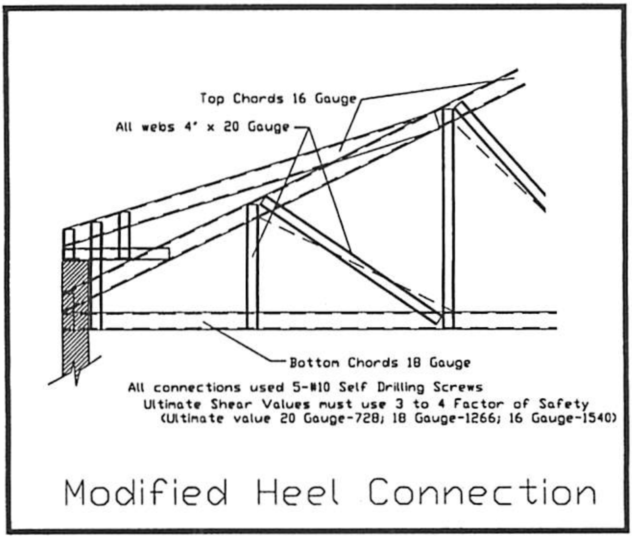


Figure 3
This was the field modification that the engineer of record designed and helped to modify in the field.

the revised end condition. The condition, shown in Figure 3, was the revised condition erected at the home. The original simple truss consisted of common triangles but was modified at one end heel connection by adding some indeterminate elements that seriously challenged the critical heel connection.

A hand generated graphical analysis was used to determine the loads in each member (See Figure 1) and therefore each joint. The member stresses were matched to the member stresses the engineer of record had shown on his "shop drawing". The field modification was supervised by the design/fabrication engineer of record. The engineer of record emphatically asserted that when analyzed in total, the loads dissipate to the other members of the truss.

After the hearing and final judgement by the board, the board's consultant specifically asked W. C. Bracken to analyze the end connection modification, using a finite element analysis. The further analysis was to determine if the revised connection met the Standard Building Code requirements for wind load. The Bracken generated finite element analysis confirmed the serious overstress created by this field modification, by the engineer of record.

This presentation used a finite element analysis by Bill Bracken, PE to demonstrate how this impressive sounding analytical tool can, and was being mis-used to deceive those responsible for assuring a sound building. The engineer was acquitted of all charges because the board's expert failed to do a complete analysis of all the joints of the entire truss. The board's engineer analyzed and provided standard calculations to demonstrate that the heel connection provided only 26% of the capacity required and therefore would fail during the code mandated wind loads. The design engineer of record, testified that those heel connection loads were much less when the truss was fully analyzed.

Finding

The administrative judge recommended, to the Florida Board of Engineers, that the engineer be found *'not guilty of incompetence and negligence'* in this case. The Florida Board of Engineers, following the recommendation of the administrative judge, found the engineer of record **"NOT GUILTY of incompetence and negligence".**

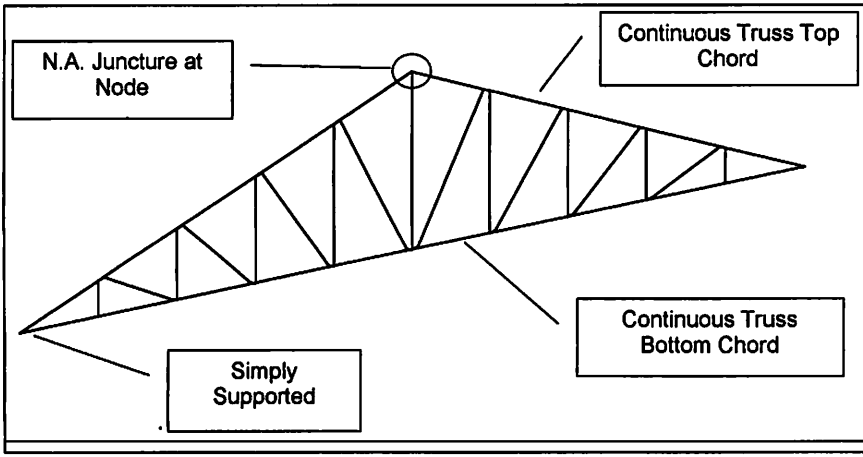
Technical Supplement to the Pre-Trial Investigations & Findings

Scope of the Post-Trial FE Analysis

The post-trial FE analysis was conducted to further evaluate and assess the propriety of the design engineer's assertions with respect to the truss heel and support condition. The post-trial FE analysis consisted of modeling and evaluating the original design based on the idealized constraints and conditions as well as modeling and evaluating the as-built heel & support conditions. Once the two conditions were modeled the specified design loads were applied and the heel & support conditions were evaluated. Of particular note were the design engineers assertions that by modifying the design to meet installation constraints and then performing a FE analysis, the shear within the heel dissipated and no longer constituted a design consideration. The post-trial FE Analysis was preformed with the aid of specialized finite element modeling and analysis software STADD III.

Design Engineer's Idealized Method

The original method utilized by the design engineer was based on a standard pre-engineered wood truss approach and later justified by a complex FE analysis. Both approaches were marked by the following assumptions: all of the truss members were rectangular and prismatic; the neutral axes, shear centers and connection were found in a single plane; the top & bottom chords remained continuous & uninterrupted and the heel & support conditions were simple pinned supports. The post-design FE analysis conducted by the design engineer allegedly served to support his assertion that the simplified method was "over designed" and that "the heel connection no longer has shear, but rather only simple rotation".



Finite Element (FE) Analysis Method

Finite Element Analysis is a tool used by structural engineers to simulate structures through mathematically generated models. The theory behind Finite Element Analysis is to break the structure, and its elements, into smaller, discrete elements. This is done to be able to analyze an element at more points of interest than the ends and midpoint. Using this method, a 20 ft. beam or column may be divided into 10 – 2 foot. sections for purpose of analysis. Finite Element Analysis programs can be used in two separate, but equally valuable, applications. They can be used for analysis of existing structures for determination of forces in elements of the structure. They can also be utilized to allow the computer to determine element sizes by inserting the geometry, load, and support conditions of the structure.

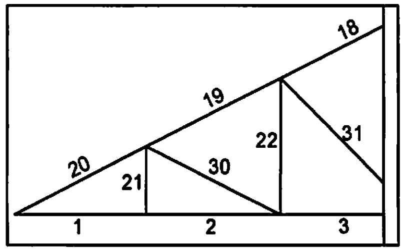
It is important to note that each segment of the model is assigned properties equal to the elements they represent, (i.e. Beams, Columns, Walls, Slabs, et al). Member offsets, partially restrained joints, pattern loadings, and member size determination are a few of the parameters that can be incorporated through the use of Finite Element Analysis. These properties are used to determine relative stiffness and ultimately the stress imposed and/or absorbed by each respective member. Stiffness analysis is accomplished through the use of both linear and nonlinear analyses. This analysis then results in numerical and graphical results. Member forces, member stresses, joint displacements, and support reactions are a few of the many values obtained through a Finite Element Analysis. It follows that manipulation of these properties can significantly affect the outcome of the model.

Finite Element (FE) Analysis Procedure

Finite Element models are created through the following procedure:

1. Coordinates are assigned to all nodes of the structure based on a 3-dimensional Cartesian coordinate system. Nodes are numbered according to a numbering scheme so in order for members, loads, and supports can be placed.

2. Members are created through the connection of two or more nodes, according to their assigned numbers. Two nodes are connected to create a beam, four for a plate element, and eight for a solid element. Elements are numbered according to a scheme.



3. Member offsets and member releases can be inserted to achieve a closer approximation of the structure. This portion of the modeling process is critical to achieving accurate results.

4. Member properties are assigned to each element of the structure. Member properties include, but are not limited to, Cross-sectional Area, Moment of Inertia, and Torsional Rigidity.

5. Material constants are assigned to each element of the structure. Material constants include, but are not limited to, Modulus of Elasticity, Coefficient of Thermal Expansion, and Density.

6. Support conditions are established, according to joint numbers. This portion of the modeling process is also critical to achieving accurate results.

7. Load patterns are established, according to joint and/or member numbers.

8. The analysis is performed. Either linear or nonlinear analysis may be used.

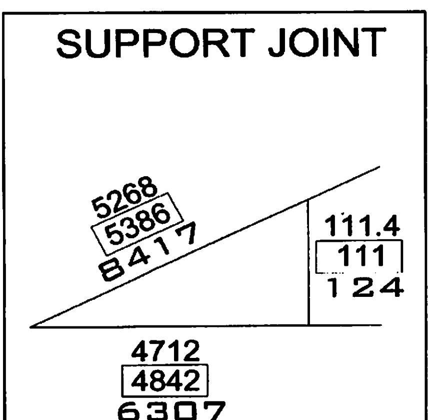
9. Analysis output is obtained through both numerical and graphical means.

Design & Analysis Verification

Engineer Yaxley, while investigating the propriety of the design engineers claims, performed a simplified graphical method of analysis that yielded results contrary to those of the design engineer's. Engineer Yaxley then engaged Engineer Bracken to perform an independent FE analysis. Engineer Bracken, utilizing the method and procedure outlined above found Engineer Yaxley's results and findings to be correct. For purposes of presentation a graphical summary of the findings has been presented below. This summary clearly depicts the fact that the design engineer's computer results varied from those computed by Engineer Yaxley and Bracken by as much as 54%.

MEMBER FORCE COMPARISON

MEMBER NO.	POST-CONSTRUCTION ANALYSIS HAND CALCS	COMPUTER ANALYSIS	AVERAGE	% DIFFERENCE	ORIGINAL DESIGN COMPUTED STRESSES	SECTION AREA	ORIGINAL DESIGN	% DIFF. FROM AVG.
	(LB)	(LB)	(LB)	%	(PSI)	(IN^2)	(LB)	%
1	4712	4842	4777	2.68%	25430	0.248	6306.6	24.25%
2	4712	4842	4777	2.68%	25430	0.248	6306.6	24.25%
3	4190	4332	4261	3.28%	23781	0.248	5897.7	27.75%
4	3667	3835	3751	4.38%	22132	0.248	5488.7	31.66%
5	3144	3342	3243	5.92%	20483	0.248	5079.8	36.16%
6	3144	3342	3243	5.92%	20483	0.248	5079.8	36.16%
7	3667	3835	3751	4.38%	22132	0.248	5488.7	31.66%
8	4190	4332	4261	3.28%	23781	0.248	5897.7	27.75%
9	4712	4842	4777	2.68%	25430	0.248	6306.6	24.25%
10	4712	4842	4777	2.68%	25430	0.248	6306.6	24.25%
11	5268	5386	5327	2.19%	28437	0.296	8417.4	36.71%
12	4685	4828	4756.5	2.96%	26957	0.296	7979.3	40.39%
13	4100	4274	4187	4.07%	25476	0.296	7541.5	44.48%
14	3515	3724	3619.5	5.61%	23999	0.296	7103.7	49.05%
15	2930	3176	3053	7.75%	22519	0.296	6665.6	
16	2930	3176	3053	7.75%	22519	0.296	6665.6	
17	3515	3724	3619.5	5.61%	23999	0.296	7103.7	49.05%
18	4100	4274	4187	4.07%	25476	0.296	7541.5	44.48%
19	4685	4828	4756.5	2.96%	26957	0.296	7979.3	40.39%
20	5268	5386	5327	2.19%	28437	0.296	8417.4	36.71%
21	111.4	111	111.2	0.36%	717	0.173	124.0	10.35%
22	372	409	390.5		2113	0.173	365.5	6.83%
23	634	689	661.5	7.98%	3608	0.173	624.2	5.98%
24	897	970	933.5	7.53%	4804	0.173	831.1	12.32%
25	2206	2392	2300	7.69%	11884	0.173	2055.9	11.87%
26	897	970	933.5	7.53%	4804	0.173	831.1	12.32%
27	634	689	661.5	7.98%	3608	0.173	624.2	5.98%
28	372	409	390.5		2113	0.173	365.5	6.83%
29	111.4	111	111.2	0.36%	717	0.173	124.0	10.35%
30	583	591	587	1.35%	3121	0.173	539.9	8.72%
31	738	762	750	3.15%	3848	0.173	665.7	12.66%
32	944	990	967	4.65%	6033	0.173	1043.7	7.35%
33	1171	1242	1206.5	5.72%	6242	0.173	1079.9	11.73%
34	1171	1242	1206.5	5.72%	6242	0.173	1079.9	11.73%
35	944	990	967	4.65%	6033	0.173	1043.7	7.35%
36	738	762	750	3.15%	3848	0.173	665.7	12.66%
37	583	591	587	1.35%	3121	0.173	539.9	8.72%
			AVERAGE DIFFERENCE =	4.60%			AVERAGE DIFFERENCE =	24.37%



It was further established that by simple free body analysis of the heel and support condition, the shear transfer through the joint was equal to the axial forces in the bottom chord at the support joint. In general terms, the design engineers assertion that the simplified method was "over designed" and that "the heel connection no longer has shear, but rather only simple rotation" were proven to be false.

As-Built Heel & Support Condition Modifications

The balance of the Finite Element Analysis consisted of modeling and evaluating the as-built & as-modified conditions. These conditions yielded results to support the original investigative findings and to refute the assertions and conclusions offered by the design engineer at trial. More specifically, top chord members were found to be in tension, bottom chord members were found to be in compression and web members were found to be in bending. Therefore, the sufficiency of the design and the assertions and conclusions offered by the design engineer at trial ultimately were found to be erroneous.