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Neuro-Fuzzy Modeling For Web Crippling Strength Of Cold-Formed Steel Sheeting

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IN

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BY

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Neuro-Fuzzy Modeling For Web Crippling Strength
Of Cold-Formed Steel Sheeting

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Supervisor

Assoc. Prof. Dr. AbdulkadirÇEVİK

by

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Ekrem CAN

ABSTRACT

NEURO-FUZZY MODELING FOR WEB CRIPPLING STRENGTH OF COLD-FORMED STEEL SHEETING

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This study presents unified rule-based modeling for web crippling strength of cold-formed steel sheeting for various loading cases using neuro-fuzzy approach. The proposed Neuro-fuzzy model used for is based on well established experimental results from the literature. The results of the proposed NF model are also compared with results of existing design codes are found to be more accurate.

Keywords: Web crippling, cold-formed steel, sheeting, neuro-fuzzy

ÖZET

SOĞUKTA İŞLENMİŞ ÇELİK TABAKALARIN GÖVDE EZİLME DAYANIMLARININ BULANIK MANTIK İLE MODELLENMESİ

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Şubat
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Bu çalışma soğukta işlenmiş çelik tabakaların gövde ezilme dayanımlarının kural bağımlı bulanık mantık modelllenmesidir. Önerilen bulanık mantık modeli literatürden toplanan güvenilir deney sonuçlarına dayalı olarak geliştirilmiştir. Önerilen bulanık mantık modelinin sonuçları mevcut tasarım kodlarının sonuçları ile karşılaştırılmış ve daha doğru sonuç verdiği görülmüştür.

Anahtar kelimeler: Gövde ezilmesi, soğukta işlenmiş çelik, kaplama, bulanık mantık

To My Family

ACKNOWLEDGEMENTS

I would like to express my respect and regards to my supervisor, Assoc. Prof. Dr. Abdulkadir Çevik, my co-supervisor his guidance, advice, encouragement and suggestions during the preparation of this thesis.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Since the early 1940's, thin-walled cold-formed steel structural members have gained increasing use in building construction, especially for low rise buildings, residences, and for many other different types of structural framing systems. This trend will continue in the futurebecause cold-formed steel members can provide an economical design for relatively light loads or short spans. In addition, unusual sectional configurations can be easily produced by the cold-forming process, and a large strength-to-weight ratio can be obtained for cold-formed steelsections. (Davies and Yu, 1972)

Cold-formed steel sections used in structures, developed over the past half century, represent an alternative to the use of relatively massive hot rolled sections in application where light weight sections can be used. Although the use of cold-formed steel in construction has been known since themiddle of the last century, the large scale use of light gauge cold formed steel members in buildings started around 1940. Today it is widely used in framing as studs and joists, in storage racks, and in other structural and semi-structural items.Among the advantages that cold-formed structural members have over hot rolled shapes are:

1. For short spans and for light loads, cold-formed members are cheaper and lighter.

2. Changing the profile requires less expensive tooling and consequently more favourable strength-weight ratios can be achieved in specific application.

3. Structural elements can be formed which provide useful surfaces, such as decks and walls, and, using pre-painted sheet, can give an attractive finished construction.

4. Edge stiffeners are not easy to incorporate in hot-rolled shapes but provides no problem in cold-formed members (Troll 1992).

A wide variety of shapes is produced by cold forming (see Figure 1.1), many of which find use in building construction because of the following advantages over wood:

1. Termite and rot proof.
2. Non-combustible.
3. Non-shrinking and non-creeping at ambient temperature.
4. Uniform quality.
5. They can be welded, bolted, riveted, as well as screwed and nailed.
6. Holes can be provided in the web to allow wiring, piping and stabilizing transverse channels to pass through, (see Figure 1.2). The present study deals with local buckling in cold-formed lipped channels (Troll 1992).

Numerical and experimental research on cold-formed steel members still remains to be an active area due to significant advantages they offer such as: high strength/weight ratio, ease of transportation and construction, mass production, and faster installation. Web crippling which is a significant failure type for cold-formed steel members is an important area of research in this field. The theoretical background of web crippling behaviour is very complicated which leads expressions used in design codes to be empirical equations based on experimental studies (Winter and Pian 1946, Baehre 1975, Hetrakul and Yu 1978, Yu 1981, Studnicka 1990, Gerges 1997, Avci and Easterling 2002, Wing 1981, Bhakta et al 1992, Wu et al 1997).

There have also been numerous numerical studies on web crippling behaviour covering Finite elements (Santaputra 1986, Sharp 1990, Landolfo 1995, Vaessen 1995, Talja 1992,Davies and Jiang 1997) and so-called mechanical models (Bahr 1978, Bakker 1992, reinsch 1983, Tsai and Crisinel 1996, Hofmeyer 2000). Alternative to these experimental and numerical researches Cevik has recently introduced soft computing techniques to model and formulate web crippling strength of cold-formed sheeting. As a part of his PhD thesis (Cevik 2006),Cevik has first introduced Neural networks (Guzelbey et al 2006) followed by genetic Programming (Cevik 2006) and Stepwise regression (Cevik 2007) approaches regarding web crippling strength of cold-formed sheeting.

This study aims to propose a new empirical rule-based approach for the prediction web crippling strength of cold-formed steel sheeting namely as Neuro-fuzzy (NF) for the first time in literature. Experimental database used for NF training and testing are collected from literature. A single NF model is proposed to cover all loading cases at the same time. Results of the NF model are furthermore compared with existing design codes and are seen to be more accurate.

1.2 Layout of The Thesis

In present work main attention is focused on web crippling strength of cold-formed steel sheetings. The main goal of the study is to propose a new empirical rule-based approach for the prediction web crippling strength of cold-formed steel sheetings. The organization of the study and the layout of the thesis isas follows:

- Chapter 2 is the literature survey on web crippling strength strength of cold-formed steel sheetingsin theoretical and experimental areas. Recent studies on design code formulations are discussed in this chapter.

- Chapter 3 is devoted to the Fuzzy Logic. The basic theory on Neuro fuzzy approach is presented in this chapter.

- Chapter 4 presents the numerical application of neuro-fuzzy modeling of web crippling strength of cold-formed steel sheetings.

- Finally in Chapter 5, some brief conclusions are presented together with some suggestions for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Current Design Codes

In the design of steel buildings, the "Allowable Stress Criteria" have long been used for the design of cold-formed steel structural members in the United States and other countries. On the other hand, in view of the fact that the mathematical theory of probability, which has been so successfully applied in other fields of engineering, would seem to be equally applicable to cold-formed steel design by providing a more uniform degree of structural safety, the "Limit State Design" method based on the probabilistic concept has been used in Canada and Europe for the design of cold-formed steel structural members.(Yu et al. 1988)

During the period of October 1968 through September 1980,the 1968 Edition of the AISI Specification was used for the design of steel deck webs that could withstand web crippling and combined web crippling and bending.^ The design formulas used to prevent web crippling were developed primarily on the basis of tests conducted in the 1940's and 1950's at Cornell University.(Yu 1981)

Recently, new types of cold-formed steel sections have been developed and used in building construction. The use of unusual geometric configurations has complicated the design of such members. In order to develop new design criteria, additional studies of the crippling strength of beam webs have been made in several countries. (Yu 1981)

In 1973, a research project on a study of beam webs has begun at the University of Missouri-Rolla (UMR) under the sponsorship of American Iron and Steel Institute. Based on the available test data obtained from research at Cornell and tests recently conducted at UMR, modified AISI design formulas for web crippling have been proposed. Because these modified formulas are based on the test data of channels, I-beams, and hat sections having vertical webs with relatively small R/t and N/t ratios, these proposed design provisions may or may not be fully suitable for the design of steel decks when they have inclined webs with large R/t and/or large N/t ratios. In addition, various types of embossments and indentations are usually formed in the webs of the steel decks to be used forcomposite slabs. These deformations may affect the web crippling strength Of steel decks. For this reason, a research project was initiated in 1979 at the University of Missouri-Rolla to study the web crippling strength of steel decks. This project was cosponsored by Steel Deck Institute, American Iron and Steel Institute, and H. H. Robertson Company. (Yu 1981)

2.2 Web Crippling in Design Codes

Web crippling failure is primarily experienced in the web element of a member and the web-flange interaction affects the resistance of this mode of failure. Stiffened and unstiffened flanges play an important role in the web crippling resistance. American Design Standard (NAS 2001), separate the sections into stiffened sections and unstiffened sections. As a result of numerous experimental research on web crippling

4 loading cases have been proposed in multi-web deck (Figure 2.1) studies and four loading conditions are introduced in NAS 2001 namely as: Exterior Two Flange (ETF), Exterior One Flange (EOF), Interior Two Flange (ITF), and Interior One Flange (IOF) loading (Figures 2-5).

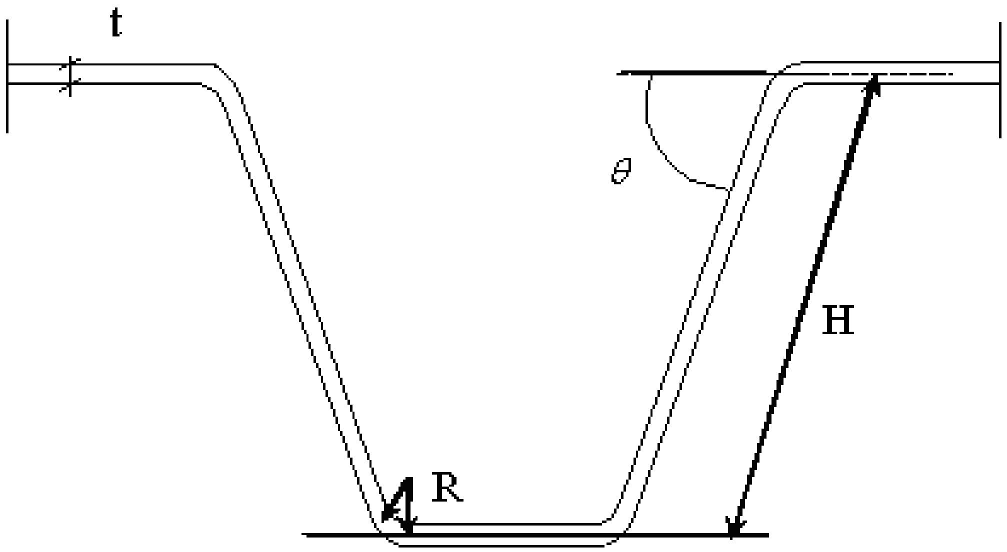

Figure 2.1.Geometry of cross-section variables.

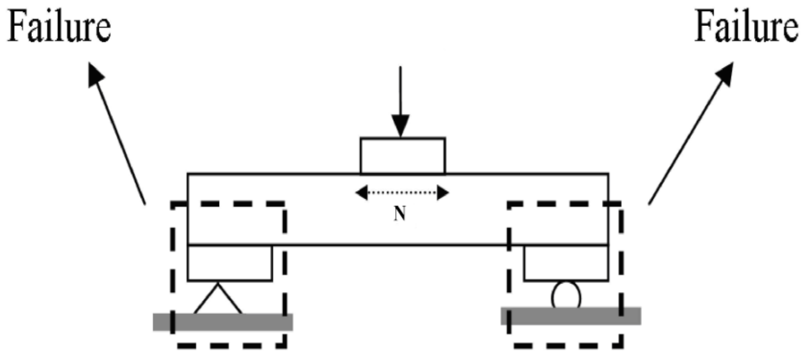

Figure 2.2 End-One-Flange Loading

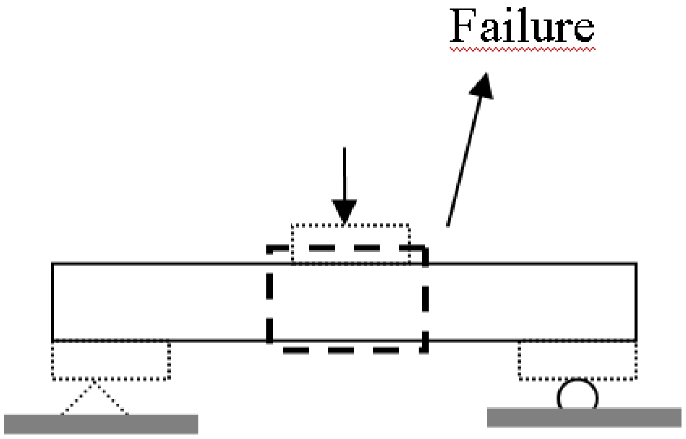

Figure 2.3 InteriorOne-Flange Loading

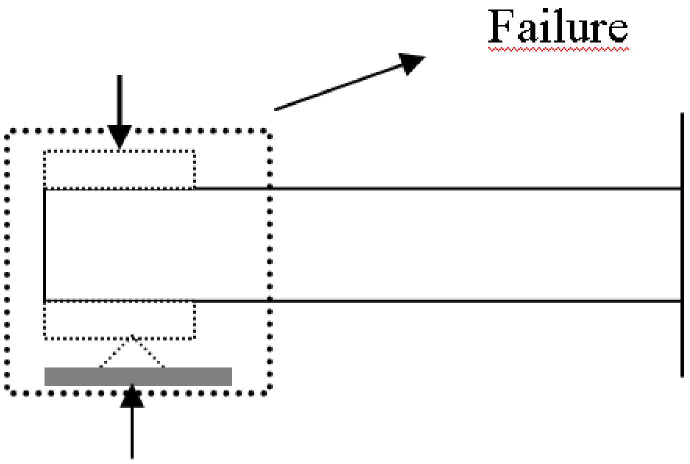

Figure 2.4 End-Two-Flange Loading

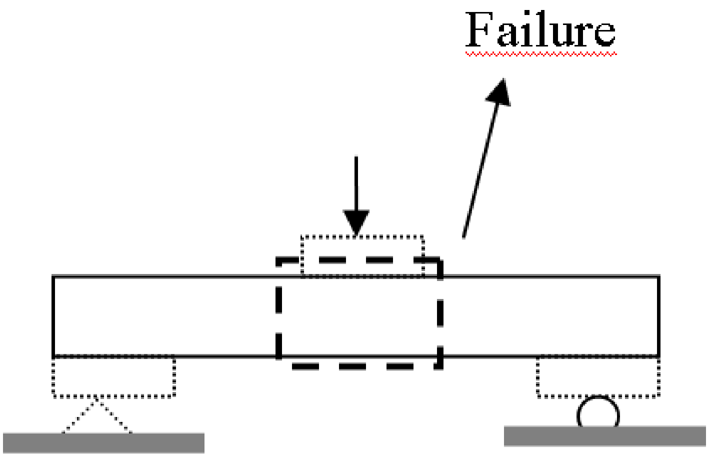

Figure 2.5 Interior-Two-Flange Loading

On the other hand Eurocode 3 introduces one category for ETF, EOF, and ITF loading and one category (category 2) for IOF loading. (EN 2004).The web crippling behaviour of cold formed steel members is directly affected by the following section parameters, which are considered proportional factors to the web crippling resistance:

- Yield strength of steel (Fy).
- Web thickness (t).
- Inside bend radius to thickness ratio (R).
- Web height to thickness ratio (H).
- Bearing length of plate to thickness ratio (N)
- Angle between the plane of the web and the plane of the bearing surface (θ)(RP00-2 2006).

Current design codes for sheeting are based on the prediction of the web crippling and bending moment resistances separately and the maximal allowable interaction of the two. The case studies in this paper deal with the prediction of web crippling resistance acting on the sheeting. The prediction of the web crippling resistance of sheeting in current design codes is based on experiments results (RP00-2 2006). The sheet sections are subjected to a concentrated load with a small bending moment which does not have a significant effect on the value of concentrated load.The ultimate load is recorded and used in the development of a web crippling predictor equation.

The formulations used in NAS 2004 are based on the following unified expression with different coefficients for design of I-sections, single web sections and multiweb sections proposed by Parabakaran (1993,1998):

$$P_n = Ct^2F_y \sin\theta(1-C_R\sqrt{R})(1+C_N\sqrt{N})(1-C_H\sqrt{H}) \qquad (2.1)$$

Geometric parameters for this equation can be seen in Figure2.1.

P_n= nominal computed ultimate web crippling load or reaction per web using new expression

C =Overall web crippling coefficient

C_h = web slenderness coefficient

C_N = bearing length coefficient

The web crippling coefficients, C, C_h , C_N and C_R are summarized in Table 2.1 which were taken from NAS 2004 .

Table 2.1. Coefficients for Multiweb sections in NAS 2004

Support Conditions	**Load Cases**		**C**	**CR**	**CN**	**CH**
FASTENED TO SUPPORT	One - Flange Loading or Reaction	End	4	0.04	0.25	0.025
		Interior	8	0.10	0.17	0.004
	Two - Flange Loading or Reaction	End	9	0.12	0.14	0.040
		Interior	10	0.11	0.21	0.020
UNFASTENED	One - Flange Loading or Reaction	End	3	0.04	0.29	0.028
		Interior	8	0.10	0.17	0.004
	Two - Flange Loading or Reaction	End	6	0.16	0.15	0.050
		Interior	17	0.10	0.10	0.046

On the other hand, according to Eurocode(EN 2004):

In cross-sections with two or more webs, including sheeting, (hat and multiweb sections), the local transverse resistance of an unstiffened web should be determined as specified, provided that both of the following conditions are satisfied:

- the clear distance *c* from the actual bearing length for the support reaction or local load to a free end is at least 40 mm;
- the cross-section satisfies the following criteria:

  $r / t \leq 10$; $h_w / t \leq 200 \sin(\theta)$; $45^0 \leq \theta \leq 90^0$

where

h_w is the web height between the midlines of the flanges;

r is the internal radius of the corners;

θ is the slope of the web relative to the flanges [degrees].

If both of these conditions are specified, the web crippling load should be determined from

$$P_n = \alpha t^2 \sqrt{F_y\ E}\,(1-0.1\sqrt{\frac{r}{t}})(0.5+\sqrt{\frac{0.02 l_a}{t}})(2.4+(\frac{\theta}{90})^2) \qquad (2)$$

l_a is the effective bearing length for the relevant category,

α is the coefficient for the relevant category described in the code (EN 2004).

Previous versions of the cold-formed steel standards regarding the web crippling equations have been recently updated to what is currently found in 2004 NAS, as a result of a study by the AISI (RP00-2 2006).

CHAPTER 3

FUZZY LOGIC

3.1 Fuzzy Logic

Over the last decade, fuzzy logic invented by Zadeh (1965) in 1965 by has been applied to a wide range of covering engineering, process control, image processing, pattern recognition and classification, management, economics and decision making (Rutkowski 2004).

Fuzzy systems can be defined as rule-based systems that are constructed from a collection of linguistic rules which can represent any system with accuracy, i.e., they work as universal approximators. The rule-based system of fuzzy logic theory uses linguistic variables as its antecedents and consequents where antecedents express an inference or the inequality, which should be satisfied and consequents are those, which we can infer, and is the output if the antecedent inequality is satisfied. The fuzzy rule-based system ia actually an IF–THEN rule-based system, given by, IF antecedent, THEN consequent (Sivandam et al 2007).

FL operations are based on fuzzy sets where the input data may be defined as fuzzy sets or a single element with a membership value of unity . The membership values(μ_1 and μ_2)are found from the intersections of the data sets with the fuzzy sets as shown in Figure 3.1 which illustrates the graphical method of finding membership values in the case of a single input (Haris 2006).

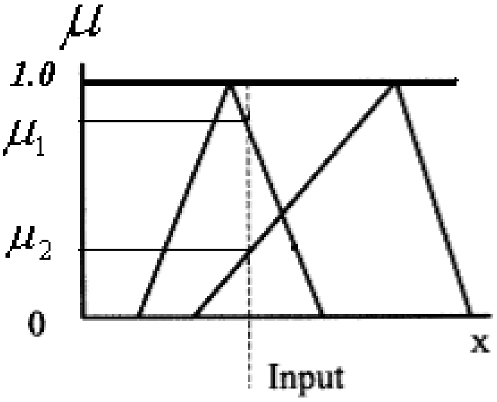

Figure3.1 Input Data Membership values

Afuzzy set contains elements which have varying degrees of membership in the set, unlike the classical or crisp sets where a member either belongs to that set or does not (0 or 1). However a fuzzy set allows a member to have a varying degree of membership and this partial degree membership can be mapped into a function or a universe of membership values (Ying et al 2006). The implementation of fuzzy logic to real applications considers the following steps (Ying et al 2006):

1. Fuzzification which requires conversion of classical data or crisp data into fuzzy data or Membership Functions (MFs)
2. Fuzzy Inference Process which connects membership functions with the Fuzzy rules to derive the fuzzy output
3. Defuzzification which computes each associated output.

3.2Neuro-Fuzzy Systems

Fuzzy systems can also be connected with Neural Networks to form neuro-fuzzy systems which exhibit advantages of both approaches .Neuro-fuzzy systems combine the natural language description of fuzzy systems and the learning properties of neural networks. Various neuro fuzzy systems have been developed that are known in literature under short names. ANFIS developed by Jang (Jang et al 1997), (Adaptive Network-based Fuzzy Inference System) is one of these Neuro-fuzzy systems which allows the fuzzy systems to learn the parameters using adaptive backpropagation learning algorithm (Rutkowski 2004).Mainly three types of fuzzy inference systems have been widely employed in various applications:Mamdani, Sugeno and Tsukamoto fuzyymoels. The differences between these three fuzzy inference systems are due to the consequents of their fuzzy rules, and thus their aggregation and defuzzification procedures differ accordingly (Jang et al 1997). In this study the Sugeno FIS is used where each rule is defined as a linear combination of input variables. The corresponding final output of the fuzzy model is simply the weighted average of each rule's output. A Sugeno FIS consisting of two input variables x and y, for example, a one output variable f will lead to two fuzzy rules:

Rule 1: If x is A_1, y is B_1 then f1 = $p_{1x} + q_{1y} + r_1$

Rule 2: If x is A_2, y is B_2 then $f_2 = p_{2x} + q_{2y} + r_2$

where pi, qi, and ri are the consequent parameters of ith rule. A_i, B_i and C_i are the linguistic labels which are represented by fuzzy sets shown in Figure 3.2

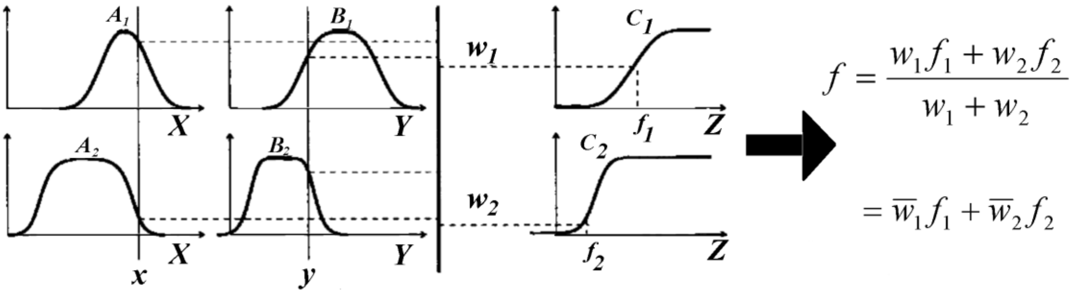

Figure3.2TheSugeno fuzzy model (Jang et al 1997).

3.3 Solving a simple problem by ANFIS

To illustrate how ANFIS works for function approximation, lets suppose one is given a sampling of the numerical values from the simple function below:

$$yi = a^3 + b^2 \quad (3.1)$$

where a and b are independent variables chosen over randomly points in the real interval [1, 9] and. In this case, a sample of data in the form of 17 pairs (a,b,yi) is given where xi is the value of the independent variable in the given interval [1, 9] and yi is the output of the function given in Eqn3.1 and presented in Table 3.1 . The aim is to construct the ANFIS model fitting those values within minimum error for Equation 3.1 by using the simplest ANFIS model that is available where the number of rules are 2 for each variable and the type of output membership function is constant. Initial and final membership values of rules for each input are given in Figures 3.3 and 3.4 respectively. Suppose one will find the output for input values of 1 and 9. The inference diagram of the proposed ANFIS model is given in Figure 3.5 for input values of 1 and 9 with corresponding values of output membership which is chosen as constant. For the first input which is 1 the value of the membership function is observed to be 1 shown on left side of Figure 3.5. For the second input which is 9 the value of the membership function is observed to be 1 again shown on left side of Figure 3.5. Thus the final output will be : 82x1=82. The exact result for a=1 and b=9 from Eqn 1 will be $y=1^3+9^2 = 82$.

Table 3.1 Data pairs for Equation 3.1

a	b	y_i
1	3	10
3	4	43
5	1	126
2	6	44
7	8	407
8	7	561
1	2	5
9	4	745
2	5	33
7	8	407
1	1	2
9	9	810
1	9	82
9	1	730
1	3	10
3	4	43
1	1	2

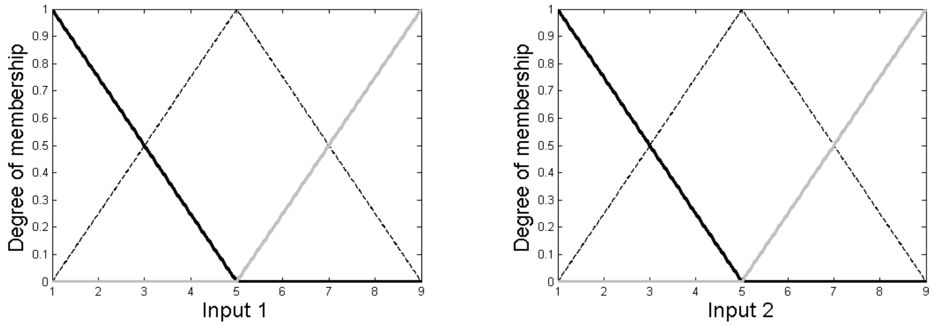

Figure3.3 Initial Membership Functions

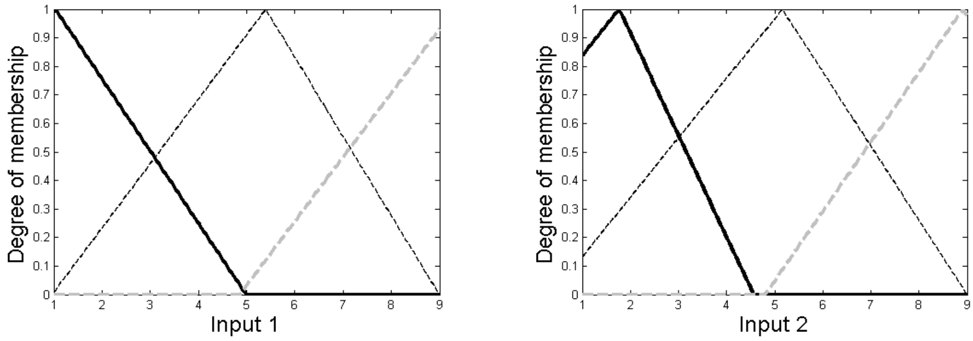

Figure3.4 Final Membership Functions

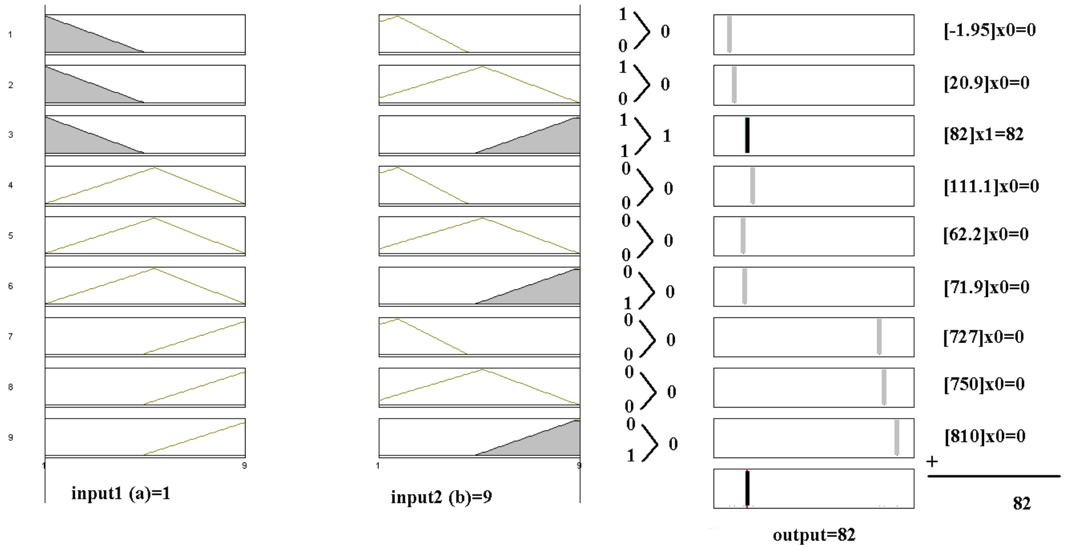

Figure3.5. Fuzzy Inference Diagram

CHAPTER 4

NUMERICAL APPLICATION

4.1 Introduction

The main aim of this article is the NF modeling of web crippling strength of cold-formed steel sheeting based on experimental results collected from literature. Among various experimental studies the experimental database used for the development of new coefficients for multiweb decks in NAS 2004 has been taken.The experimental database including the ranges of parameters where the proposed NF model will be valid are given in Table 4.1. The sheet section variables used in these experimental studies is given in Table 4.1. Four different loading cases regarding fastened ETF, EOF, IOF and ITF have been considered as a single unified NF model in this study. The loading cases have quantified as CL = 1 for ETF; CL = 2 for ITF; CL = 3 for IOF; CL = 4 for EOF for NF modeling process. The experimental database presented in Tables A1-A4 has been used for training (155 tests) and testing set (39 tests) of the proposed NF model where bold tests have been used as testing set. The NF model is constructed with training sets and the accuracy is verified by testing sets which the NF model faces for the fist time.

4.2 Results and Disscussions

To illustrate the effectiveness of the NF approach, the simplest ANFIS model is selected. The proposed ANFIS model uses Triangular input membership functions with minimum number of rules which is 2. The output membership function is chosen as the simplest one available which is a constant value. These conditions will lead to the simplest available NF model. Statistical parameters of the proposed ANFIS model for Test/Predicted results are compared with existing design codes for all loading cases are given in Table 4.2. The initial and final membership functions for inputs are presented in Figures 4.1 and 4.2 respectively. Features of the proposed ANFIS model are given in Table 4.3. Output membership function values are given in Table 6. The performance and accuracies of Mean (Test/ANFIS) for training, testing sets and in overall are presented in Figures4.3-4.5.

Table 4.1 Experimental Database of multiweb deck sections used in the study (RP00-2 2006)

Section		Researcher's Name	No. of Points	t min to t max (mm)	Fymin to Fymax (MPa)	h/t min to h/t max (ratio)	r/t min to r/t max (ratio)	n/t min to n/t max (ratio)
a) Fastened	1) EOF	Bhakta, 1992	2	0.660 to 0.660	396.0 to 396.0	102.8 to 102.9	6.6 to 6.6	101.0 to 101.0
	2) IOF	Wing, UW, 1981	34	0.508 to 1.549	230.8 to 317.5	72.3 to 207.2	1.5 to 13.0	16.4 to 161.9
		Bhakta, 1992	2	0.660 to 0.660	396.0 to 396.0	102.8 to 102.9	6.6 to 6.6	201.9 to 201.9
	3) ETF	Wing, UW, 1981	63	0.610 to 1.575	230.8 to 337.5	20.6 to 324.3	1.3 to 10.1	16.4 to 125.0
	4) ITF	Wing, UW, 1981	57	0.610 to 1.539	230.8 to 337.5	20.6 to 207.2	1.3 to 10.0	16.7 to 125.0
b) Unfastened	1) EOF	Yu, 1981	18	0.721 to 1.240	270.7 to 343.7	38.0 to 99.3	3.1 to 7.1	61.1 to 208.1
		Bhakta, 1992	2	0.660 to 0.660	396.0 to 396.0	102.7 to 102.9	6.6 to 6.6	101.0 to 101.0
		Wu et al. 1997	16	0.432 to 0.737	715.7 to 774.9	25.9 to 208.3	2.2 to 5.5	34.5 to 58.8

Table 4.2 Statistical parameters of NF Model compared with current design codes

Loading Case		**Mean (Test/Predict.)**	**Standard Deviation**	**C.O.V**
ETF	EUROCODE	1.19	0.32	0.27
	NAS 2004	1.00	0.15	0.15
	NF	0.97	0.11	0.11
ITF	EUROCODE	1.03	0.16	0.15
	NAS 2004	1.01	0.11	0.11
	NF	1.04	0.10	0.09
IOF	EUROCODE	1.34	0.48	0.36
	NAS 2004	1.02	0.13	0.12
	NF	1.01	0.16	0.15
EOF	EUROCODE	1.27	0.25	0.19
	NAS 2004	1.00	0.34	0.34
	NF	0.96	0.14	0.15
OVERALL (ALL LOADING CASES)	**EUROCODE**	**1.19**	**0.29**	**0.24**
	NAS 2004	**1.00**	**0.17**	**0.17**
	NF	**1.00**	**0.13**	**0.13**

Table 4.3 Features of the proposed ANFIS model

Type	SUGENO
Aggregation Method	Maximum
Defuzzification Method	Weighted Average
Input Membership Function Type	Triangular
Output Membership Function Type	Constant

Table 4.4 Values of Output Membership functions (128 Constant Output MeF)

Mef 1= -4.50	MeF 17 = 32.88	MeF 33 = 4.59	MeF 49 = 4.67	MeF 65 = 2.71	MeF 81 = -16.25	MeF 97= 7.69	MeF 113 = 37.49
MeF 2= 2.04	MeF 18 = -95.26	MeF 34 = 6.47	MeF 50 = 98.68	MeF 66 = -1.37	MeF 82 = 34.31	MeF 98= 12.04	MeF 114 = -85.28
MeF 3= 64.97	MeF 19 = -285.6	MeF 35 = -16.70	MeF 51 = -212.6	MeF 67 = 2.64	MeF 83 = 25.61	MeF 99= 12.19	MeF 115 = 149.40
MeF 4= 33.55	MeF 20 = 49.43	MeF 36 = 17.78	MeF 52 = -193.5	MeF 68 = -16.7	MeF 84 = -33.37	MeF 100 = -59.09	MeF 116 = 296.00
MeF 5= -26.48	MeF 21 = 145.70	MeF 37 = 51.36	MeF 53 = -200.4	MeF 69 = -1.71	MeF 85 = 16.60	MeF 101 = -56.48	MeF 117 = 198.30
MeF 6= 9.34	MeF 22 = -56.08	MeF 38 = -50.76	MeF 54 = 169.20	MeF 70 = 27.81	MeF 86 = -113.7	MeF 102 = 62.91	MeF 118 = 21.29
MeF 7= 38.75	MeF 23 = -98.90	MeF 39 = 210.10	MeF 55 = -54.08	MeF 71 = -1.10	MeF 87 = 83.78	MeF 103 = -26.57	MeF 119 = -99.94
MeF 8= -22.74	MeF 24 = -78.46	MeF 40 = 97.97	MeF 56 = -76.59	MeF 72 = -11.0	MeF 88 = 135.00	MeF 104 = 134.50	MeF 120 = -175.5
MeF 9= -2.13	MeF 25 = -38.22	MeF 41 = -0.92	MeF 57 = 61.23	MeF 73 = 5.06	MeF 89 = 28.33	MeF 105 = 2.14	MeF 121 = -168.6

Me 10 F = -7.24	Me 26 F = 344.60	Me 42 F = 6.37	Me 58 F = -380.9	Me 74 F = -2.99	Me 90 F = -40.36	Me 106 F = 5.07	Me 122 F = 202.60
Me 11 F = 35.60	Me 27 F = -49.94	Me 43 F = 368.70	Me 59 F = 45.91	Me 75 F = -12.4	Me 91 F = -36.38	Me 107 F = -216.0	Me 123 F = -123.0
Me 12 F = -264.6	Me 28 F = 115.60	Me 44 F = -10.07	Me 60 F = -16.77	Me 76 F = 86.92	Me 92 F = 64.75	Me 108 F = 423.40	Me 124 F = -87.90
Me 13 F = 11.08	Me 29 F = -9.85	Me 45 F = -190.8	Me 61 F = -10.82	Me 77 F = -20.2	Me 93 F = 43.89	Me 109 F = 193.70	Me 125 F = 96.11
Me 14 F = 41.66	Me 30 F = 81.91	Me 46 F = 59.03	Me 62 F = -28.99	Me 78 F = -9.69	Me 94 F = -80.01	Me 110 F = -231.4	Me 126 F = -17.54
Me 15 F = -61.05	Me 31 F = -51.98	Me 47 F = 38.44	Me 63 F = 5.02	Me 79 F = 45.08	Me 95 F = -58.95	Me 111 F = -173.7	Me 127 F = -114.1
Me 16 F = 233.90	Me 32 F = 36.67	Me 48 F = 164.90	Me 64 F = 17.15	Me 80 F = -83.4	Me 96 F = -64.05	Me 112 F = -446.4	Me 128 F = -188.8

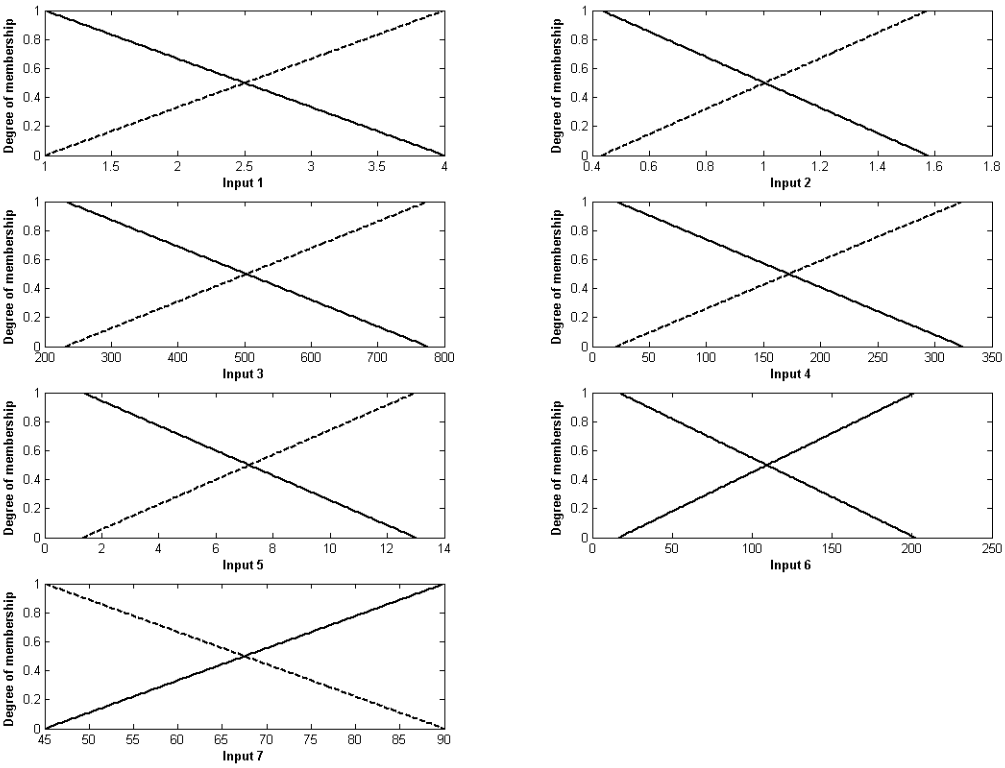

Figure 4.1. Initial Membership Values (input1=Loading case where 1,2,3 and 4 referto ETF, ITF, IOF and EOF respectively; input2= t(mm); input2= t(mm); input3= Fy(MPa); input4= H; input5= R; input6=N; input7=θ)

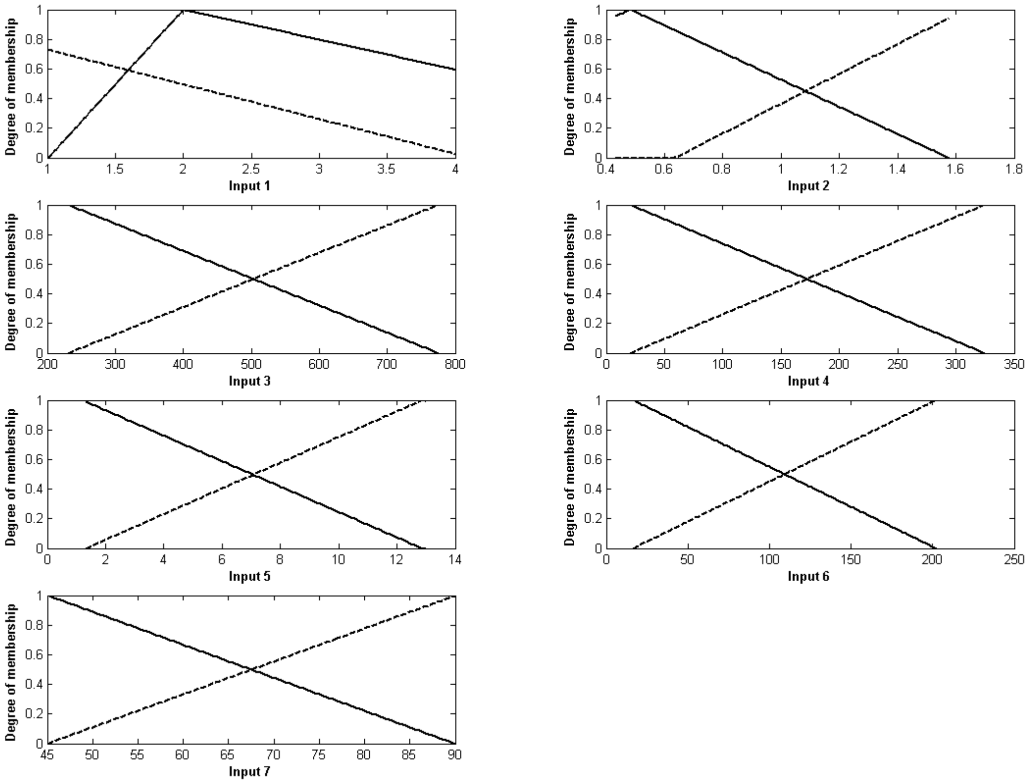

Figure4.2. Final Membership Values (input1=Loading case where 1,2,3 and 4 referto t ETF, ITF, IOF and EOF respectively; input2= t(mm); input2= t(mm); input3= Fy(MPa); input4= H; input5= R; input6=N; input7=θ)

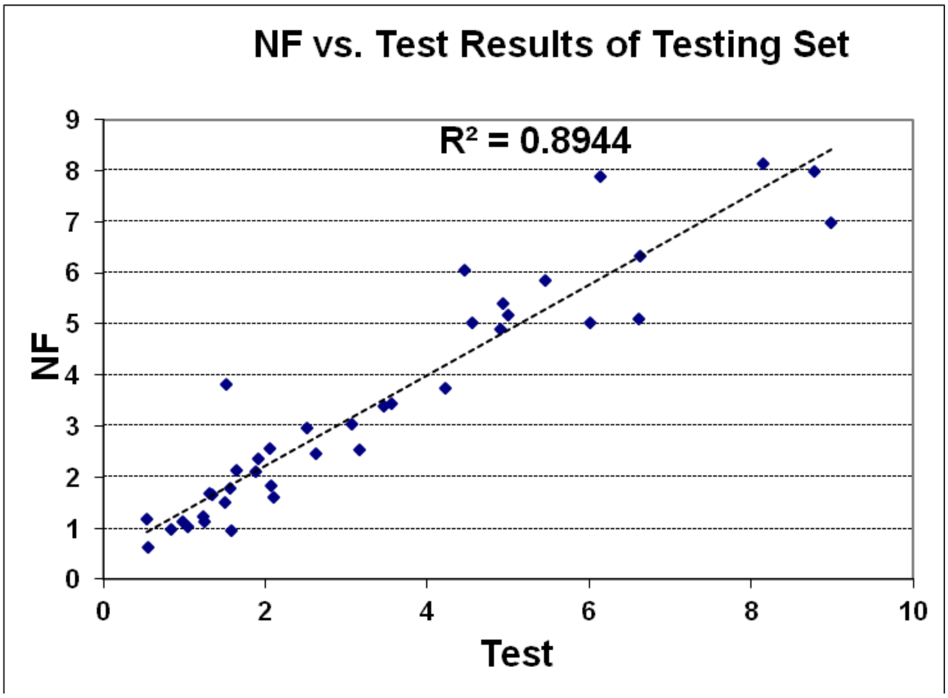

Figure4.3. Test vs. NF results of Testing Set

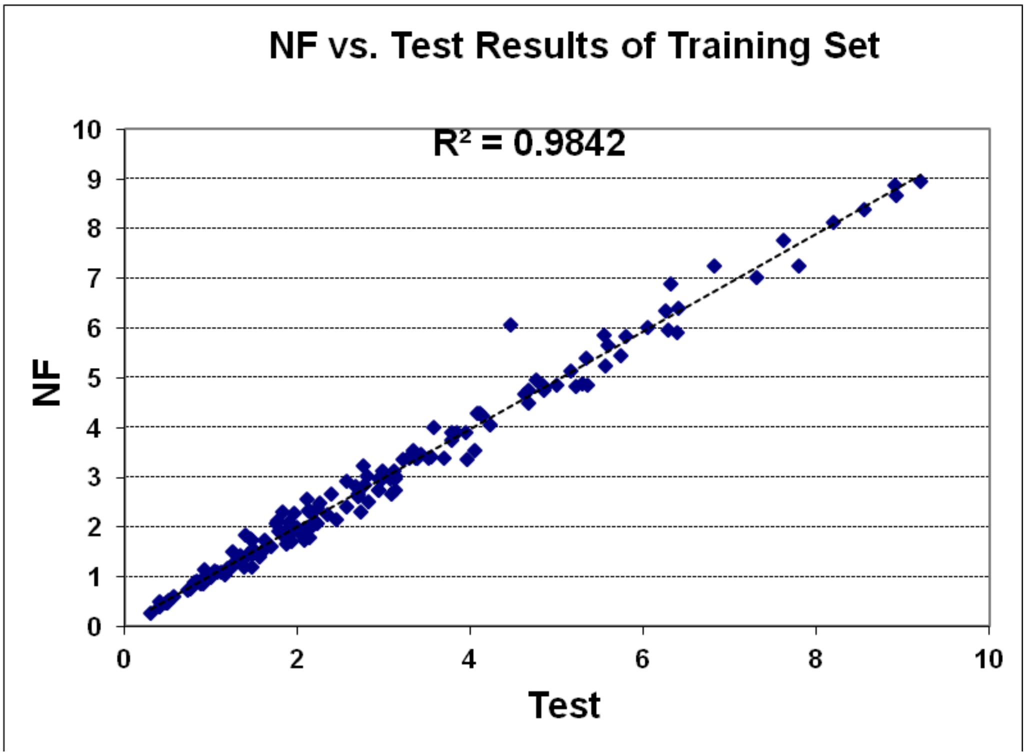

Figure4.4. Test vs. NF results of Training Set

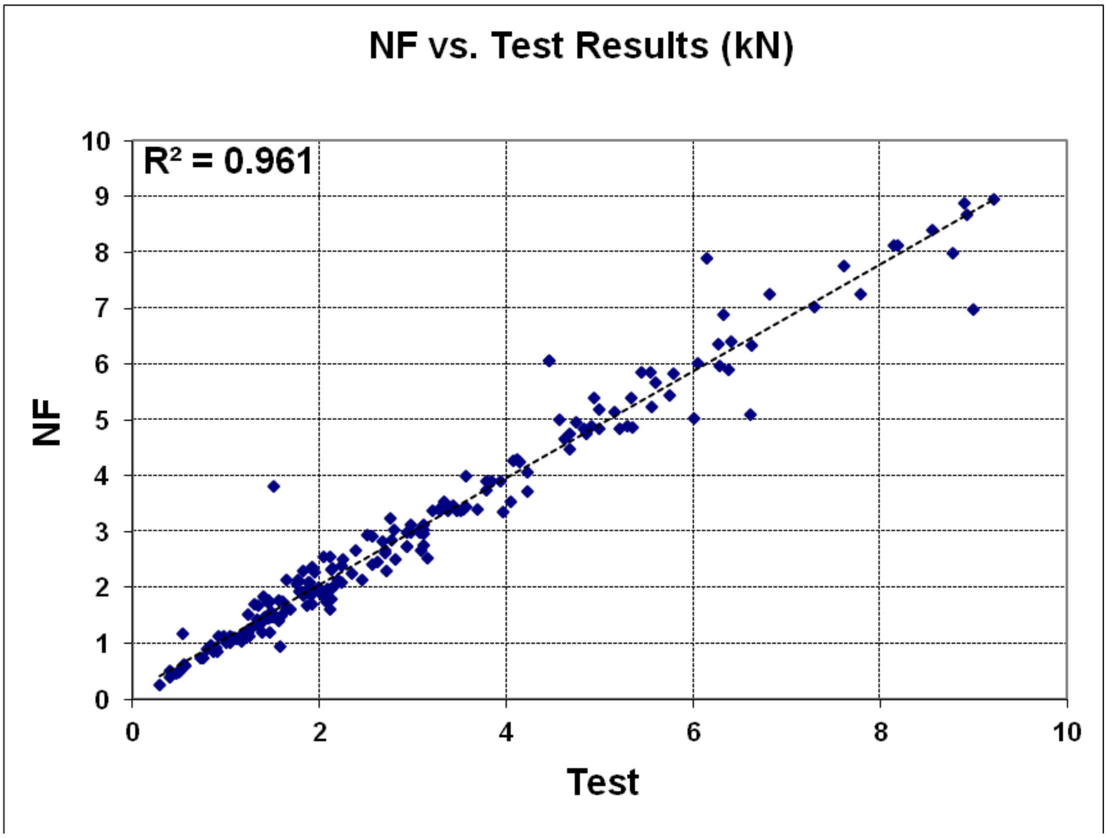

Figure4.5. Test vs. NF results in overall

The prediction of the proposed NF model vs. actual experimental values and their comparison with existing design codes (Eurocode and NAS 2004) are given in Tables A1-A4 for loading cases considered.

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

In this chapter, the general conclusion is explained built on the concepts displayed in previous chapters.

Application of Neuro-fuzzy aproach in structural engineering problems is very scarce. This thesis presents a pioneer work in this field for the modeling of web crippling strength of cold-formed steel sheeting using Neuro-fuzzy approach for the first time in literature. The proposed NF model is a unified rule-based model based on well established experimental data collected from literature covering all loading cases namely as ETF, ITF, IOF and EOF at the same time. Results of the proposed NF model (COV=0.13) are also compared with existing design codes (COVNAS2004=0.17 ; COVEUROCODE=0.24) and are found to be more accurate. The porposed NF model shows very good agreement with experimental results (R2=0.96). As a conclusion of this study, Neuro-fuzzy may serve as an effective alternative tool for the modelling of various structural engineering problems in the future.

5.2 Future Work

Future work that might be proposed to expand and develop this study can be listed as follows:

1. Use of other soft computing techniques such as Support Vector Machines (SVM).

2. A new approach for the modeling of cold-formed steel structures.

3. Other failure types than web crippling for cold-formed structures can be modeled.

LIST OF REFERENCES

Avci, O. and Easterling, W.S. (2002), Web Crippling Strength of Multi-Web Steel Deck Sections Subjected to End One-Flange Loading,, M.Sc. Thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA, U.S.A.

Bähr, G. (1978) .Eine einfache Abschätzung der aufnehmbaren Endauflagerkräfte von Stahl-Trapezblechprofilen, Die Bautechnik, 388-390.

Baehre, R. (1975), Sheet Metal Panels for Use in Building Construction – Recent Research Projects in Sweden," Proceeding of the Third International Specialty Conference on Cold Formed Steel Structures, University of Missouri-Rolla, Rolla, MO, U.S.A., 383-455.

Bhakta, B.H., LaBoube, R.A, Yu, W.W., (1992), The Effect of Flange Restraint on Web Crippling Strength, Final Report, Civil Engineering Study 92-1, University of Missouri-Rolla, Rolla, Missouri, U.S.A.

Bakker, M.C.M.(1992), Web Crippling of Cold-Formed Steel Members", Dissertation Eindhoven University of Technology, The Netherlands

Çevik, A. (2006) "A New Approach for Elastoplastic Analysis of Structures: Neural Networks", PhDThesis, University of Gaziantep, Turkey

Cevik, A. (2006), "A newformulationfor web cripplingstrength of cold-formedsteelsheetingusinggeneticprogramming", *J Constr Steel Res*, 63, 867-883

Cevik, A. (2007) "UnifiedFormulationFor Web CripplingStrength Of Cold-Formed Steel Sheeting Using StepwiseRegression", *J Constr Steel Res, 63, 1305-1316* (2007)

Davis, C. S., & Yu, W. (1972). The structural behavior of cold-formed steel members with perforated elements (Doctoral dissertation, University of Missouri, Rolla.).

Davies, J.M. and Jiang, C. (1997), “Design Procedures for Profiled Metal Sheeting and Decking”, *Thin Wall Struct,* 27*,* 43-53

EN 1993-1-3 (2004), Eurocode 3: Design of steel structures, Part 1-3: General rules Supplementary rules for cold-formed members and sheeting, Brussels

Gerges, R. R., (1997) “Web Crippling of Single Web Cold Formed Steel Members Subjected to End

One-Flange Loading.” M.Sc. Thesis, University of Waterloo, Waterloo, ON, Canada

Guzelbey, I.H., Cevik, A., Erklig, A. (2006), “Prediction of web crippling strength of cold-formed steel sheeting using Neural Networks”, *J Constr Steel Res,* 62, 962–973

Haris, J. (2006)*, Fuzzy Logic Applications in Engineering Science,* Springer

Hetrakul, N. and Yu, W.W. (1978), “Structural Behaviour of Beam Webs Subjected to Web Crippling and a Combination of Web Crippling and Bending”, Final Report, Civil Engineering Study, 784, University of Missouri-Rolla

Hofmeyer, H. (2000), Report TUE-BCO-00-09 “Report on Combined Web Crippling and Bending Moment Failure of First-Generation Trapezoidal Steel Sheeting (Appendices to the thesis)”, Eindhoven University of Technology, Faculty of Architecture, Department of Structural Design, The Netherlands

Jang, JSR., Sun, CT. and Mizutani, E. (1997), *Neuro-fuzzy and soft computing.. a computational approach to learning and machine intelligence*, Prentice Hall, 1997

Landolfo, R. and Mazzolani, F. M. (1995), Comportamentoflessionale di lamieregrecate in acciaio: analisisperimentale, ConstruczioniMetalliche 29

NAS (2001), North American Specification for the Design of Cold-Formed Steel Structural Members, Washington, D.C, Edition including 2004 Supplement.

NAS (2004) Supplement to the North American Specification for the Design of Cold-Formed Steel Structures. American Iron and Steel Institute, Washington, D.C., 2004

Parabakaran, K. (1993) “Web Crippling of Cold Formed Steel Sections”, Project Report, Department of Civil Engineering, University of Waterloo, Canada

Parabakaran, K., Schuster, R.M. (1998) “Web Crippling of Cold Formed Steel Sections”, Fourteenth International Specialty Conference on Cold-Formed Steel Structures, St. Louis, Missouri, U.S.A

Reinsch, W. (1983), “Das Kantenbeulen zur rechnerischen Ermittlung von Stahltrapezblechträger“, Dissertation, Technische Hochschule Darmstadt, Germany

RP00-2, (2006), “Web Crippling Data and Calibrations of Cold Formed Steel Members”, Research Report, American Iron and Steel Institute, Revised Edition

Rutkowski L. (2004), *Flexible Neuro-Fuzzy Systems: Structures, Learning and Performance Evaluation,* Kluwer Academic Publishers

Sharp, M.L. (1990), “Design parameters for web crippling of thin-walled members”, report No. 57-90-21, Alcoa laboratories

Santaputra, C. (1986), Eighth progress report, Design of Automotive Structural Components using High Strength Sheet Steels, Web Crippling of Cold Formed Steel Beams, Civil Engineering Study 86-1, Structural Series, University of Missouri-Rolla, Department of Civil Engineering

Sivanandam, SN, Sumathi, S. and Deepa SN. (2007), *Introduction to Fuzzy Logic using MATLAB* Springer

Studnicka, J. (1990), Web crippling of wide deck sections, Recent Research and Developments in Cold-Formed Steel Design and Construction, Edited by W.W. Yu and R.A.Laboube, Rolla, University of Missouri-Rolla, Department of Civil Engineering, 317-334.

Talja, A. (1990), Design of cold-formed HSS channels for bending and eccentric compression. Bending in the plane of symmetry, VTT Research Notes 1403, Technical Research Centre of Finland

Tsai, Y.M., Crisinel, M. (1996), "Moment redistribution in continuous profiled sheeting", Thin-walled metal structures in buildings, IABSE proceedings, 49, 107-114,

Troll, F. R. C. (1992). Buckling of lipped flanges in cold-formed steel studs with web cut-outs (Doctoral dissertation, Concordia University).

Vaessen, M.J. (1995), "On the elastic web crippling stiffness of thin-walled cold-formed steel members", MSc. thesis, Eindhoven University of Technology, Department of StructuralDesign, The Netherlands

Ying Bai, Y., Zhuang, H. and Wang, D. (2006), *Advanced Fuzzy Logic Technologies in Industrial Applications,* Springer

Yu, W. W., Hsiao, L. E., &Galambos, T. V. (1988). Load and resistance factor design of cold-formed steel: Calibration of the AISI design provisions. Missouri S&T (formerly the University of Missouri-Rolla).

Yu, W.W. (1981),'"Web crippling and combined web crippling and bending of steel decks.'' Civil Engineering Study 81-2, Structural Series, University of Missouri–Rolla

Wing, B.A. (1981), “Web crippling and the interaction of bending and web crippling of unreinforced multi-web cold-formed steel sections”, Master's thesis, Waterloo, University of Waterloo

Winter, G. ,Pian, R. H. J. (1946), “Crushing Strength of Thin Steel Webs”, Cornell Bulletin 35

Wu, S.,Yu, W.W. andLaBoube, R.A. (1997), “Strength of FlexuralMembers Using Structural Grade 80 of A653 Steel (Web CripplingTests)”, CivilEngineeringStudy 97-3, ColdFormed Steel Series, Third Progress Report, University of Missouri-Rolla, Rolla, Missouri, U.S.A.

Zadeh LA. (1965), Fuzzy sets, *Information and Control,* 8, 338-353

APPENDIX

Table A1. Results of NF Model versus design codes for Fastened-End Two Flange Loading (ETF)

-----Exceeds Eurocode Limit

									EUROCODE		NAS 2004		NF	
No	Specimen	t (mm)	Fy MPa	H	R	N	θ (^{0})	Pt (kN) TEST	Pn (kN)	Pt/Pn	Pn (kN)	Pt/Pn	Pn (kN)	Pt/Pn
1	**8W-ETF**	**1.524**	**231**	**29**	**1.56**	**16.7**	**70**	**4.56**	**3.44**	**1.33**	**4.75**	**0.96**	**5.01**	**0.91**
2	9W-ETF	0.965	274	45.3	2.47	26.3	70	1.87	1.64	1.14	2.2	0.85	1.67	1.12
3	10W-ETF	0.61	265	74.3	3.91	41.7	70	0.8	0.71	1.13	0.79	1.01	0.89	0.90
4	11W-ETF	1.524	231	61.7	1.56	16.7	70	4.62	3.44	1.34	4.15	1.11	4.67	0.99
5	12W-ETF	0.965	274	98.5	2.47	26.3	69.5	1.59	1.64	0.97	1.81	0.88	1.50	1.06
6	**13W-ETF**	**0.61**	**265**	**158**	**3.91**	**41.7**	**70**	**0.55**	**0.71**	**0.78**	**0.6**	**0.92**	**0.62**	**0.89**
7	14W-ETF	1.524	231	129	1.56	16.7	69.5	3.94	3.43	1.15	3.3	1.19	3.91	1.01
8	15W-ETF	0.965	274	204	2.47	26.3	70	1.22			1.29	0.95	1.18	1.04
9	16W-ETF	0.66	265	300	3.61	38.5	71	0.4			0.44	0.91	0.40	1.01
10	17W-ETF	1.524	231	29	1.56	16.7	50.5	4.85	3.11	1.56	3.9	1.24	4.80	1.01
11	**18W-ETF**	**0.965**	**274**	**45.6**	**2.47**	**26.3**	**50.5**	**1.56**	**1.49**	**1.05**	**1.81**	**0.87**	**1.78**	**0.88**
12	19W-ETF	0.61	265	75.1	3.91	41.7	50.5	0.87	0.64	1.36	0.65	1.34	0.85	1.02
13	20W-ETF	1.524	231	63	1.56	16.7	50	3.84	3.10	1.24	3.37	1.14	3.91	0.98

14	21W-ETF	0.991	274	96.7	2.41	25.6	50	1.24	1.55	0.80	1.56	0.79	1.52	0.82
15	22W-ETF	0.635	265	153	3.75	40	50.5	0.4	0.69	0.58	0.54	0.74	0.51	0.79
16	**23W-ETF**	**1.549**	**231**	**126**	**1.54**	**16.4**	**50.5**	**1.92**	**3.20**	**0.60**	**2.82**	**0.68**	**2.37**	**0.81**
17	24W-ETF	1.016	274	194	2.35	25	51	0.9			1.22	0.74	0.86	1.05
18	25W-ETF	0.61	265	324	3.91	41.7	49.5	0.29			0.27	1.06	0.26	1.11
19	34W-ETF	0.61	265	156	3.91	41.7	90	0.56	0.80	0.70	0.64	0.86	0.59	0.94
20	35W-ETF	0.965	274	98	2.47	26.3	90	1.48	1.86	0.80	1.94	0.76	1.57	0.94
21	**36W-ETF**	**1.524**	**231**	**62**	**1.56**	**16.7**	**90**	**4.94**	**3.89**	**1.27**	**4.41**	**1.12**	**5.39**	**0.92**
22	7WR-ETF	1.539	302	57.5	5.68	33	70	4.75	4.25	1.12	5.43	0.88	4.96	0.96
23	8WR-ETF	1.539	302	52.5	7.23	33	70	4.85	4.08	1.19	5.24	0.93	4.75	1.02
24	9WR-ETF	0.627	318	191	7.59	81	50	0.51			0.58	0.88	0.52	0.99
25	10WR-ETF	0.627	318	192	10.1	81	50	0.47			0.54	0.87	0.47	1.00
26	**11WR-ETF**	**1.003**	**299**	**113**	**6.33**	**50.6**	**50**	**1.51**	**1.83**	**0.83**	**1.66**	**0.91**	**3.82**	**0.40**
27	12WR-ETF	1.539	302	74.3	5.16	33	50	4.11	3.89	1.06	4.24	0.97	4.30	0.96
28	13WR-ETF	1.003	299	114	9.49	50.6	50	1.42	1.69	0.84	1.5	0.95	1.46	0.97
29	14WR-ETF	1.539	302	72.3	6.19	33	50	4.22	3.78	1.12	4.12	1.03	4.07	1.04
30	1E-ETF	1.575	293	41.6	2.52	32.3	85	8.92	5.27	1.69	7.02	1.27	8.67	1.03
31	**2E-ETF**	**1.575**	**293**	**41.6**	**2.52**	**48.4**	**85**	**8.15**	**6.00**	**1.36**	**7.72**	**1.06**	**8.13**	**1.00**
32	1C-ETF	0.914	286	76.4	3.47	41.7	81.5	2.13	1.80	1.18	2.05	1.04	1.78	1.19
33	2C-ETF	0.914	286	76.4	3.47	55.6	81.5	2.19	1.98	1.11	2.2	1	2.14	1.02
34	3C-ETF	0.914	286	76.4	3.47	83.3	81.5	2.77	2.28	1.22	2.45	1.13	2.84	0.98
35	4C-ETF	0.914	286	76.4	3.47	111	81.5	3.33	2.53	1.32	2.66	1.25	3.54	0.94

36	**5C-ETF**	**0.813**	**282**	**85.9**	**3.91**	**46.9**	**81.5**	**1.31**	**1.45**	**0.91**	**1.56**	**0.84**	**1.69**	**0.78**
37	6C-ETF	0.813	282	85.9	3.91	62.5	81.5	1.61	1.59	1.01	1.67	0.96	1.75	0.92
38	7C-ETF	0.813	282	85.9	3.91	93.8	81.5	2.03	1.84	1.10	1.87	1.08	1.87	1.09
39	8C-ETF	0.813	282	85.9	3.91	125	81.5	1.99	2.05	0.97	2.04	0.98	1.99	1.00
40	1R-ETF	1.245	333	23.3	5.1	30.6	77.5	4.99	3.03	1.65	4.74	1.05	4.85	1.03
41	**2R-ETF**	**1.245**	**333**	**23.3**	**5.1**	**40.8**	**77.5**	**4.99**	**3.32**	**1.50**	**5.06**	**0.99**	**5.18**	**0.96**
42	3R-ETF	1.245	333	23.3	5.1	61.2	77.5	5.79	3.80	1.52	5.59	1.04	5.83	0.99
43	4R-ETF	0.635	304	49.2	10	60	77.5	1.26	0.83	2.56	1	1.26	1.27	0.99
44	5R-ETF	0.635	304	49.2	10	80	77.5	1.37	0.92	1.50	1.08	1.26	1.35	1.02
45	6R-ETF	0.635	304	49.2	10	120	77.5	1.47	1.06	1.38	1.22	1.2	1.50	0.98
46	**7R-ETF**	**1.245**	**338**	**20.6**	**5.1**	**30.6**	**66.5**	**4.91**	**2.86**	**1.71**	**4.57**	**1.08**	**4.89**	**1.00**
47	8R-ETF	1.245	338	20.6	5.1	40.8	66.5	5.15	3.13	1.64	4.88	1.06	5.15	1.00
48	9R-ETF	1.245	338	20.6	5.1	61.2	66.5	5.59	3.59	1.56	5.4	1.04	5.66	0.99
49	10R-ETF	0.66	335	38.8	9.62	57.7	66.5	1.04	0.88	1.19	1.17	0.89	1.13	0.92
50	11R-ETF	0.66	335	38.8	9.62	76.9	66.5	1.18	0.97	1.22	1.27	0.93	1.16	1.01
51	**12R-ETF**	**0.66**	**335**	**38.8**	**9.62**	**115**	**66.5**	**1.24**	**1.12**	**1.10**	**1.43**	**0.87**	**1.23**	**1.01**
52	13R-ETF	1.194	284	47.1	1.33	31.9	45	2.98	2.51	1.19	2.89	1.03	2.99	1.00
53	14R-ETF	1.194	284	47.1	1.33	42.6	45	3.54	2.75	1.29	3.09	1.15	3.41	1.04
54	15R-ETF	1.194	284	47.1	1.33	63.8	45	4.14	3.15	1.31	3.42	1.21	4.25	0.97
55	16R-ETF	0.635	336	91	2.5	60	45	0.83	0.90	0.92	0.9	0.92	0.91	0.91
56	**17R-ETF**	**0.635**	**336**	**91**	**2.5**	**80**	**45**	**1.04**	**1.00**	**1.04**	**0.97**	**1.07**	**1.02**	**1.02**
57	18R-ETF	0.635	336	91	2.5	120	45	1.25	1.16	1.08	1.09	1.14	1.23	1.02

58	25R-ETF	1.27	291	51.7	3.13	30	87.5	3.57	3.32	1.08	4.19	0.85	3.99	0.89
59	26R-ETF	1.27	291	51.7	3.13	40	87.5	4.07	3.63	1.12	4.47	0.91	4.28	0.95
60	27R-ETF	1.27	291	51.7	3.13	60	87.5	4.83	4.15	1.16	4.94	0.98	4.85	1.00
61	**28R-ETF**	**0.813**	**307**	**82.1**	**4.88**	**46.9**	**87.5**	**1.65**	**1.52**	**1.08**	**1.67**	**0.99**	**2.13**	**0.78**
62	29R-ETF	0.813	307	82.1	4.88	62.5	87.5	1.75	1.68	1.04	1.8	0.97	2.08	0.84
63	30R-ETF	0.813	307	82.1	4.88	93.8	87.5	2.13	1.94	1.10	2.01	1.06	1.98	1.08
								Mean		1.19		1.00		0.97
								StdDev		0.32		0.14		0.11
								C.O.V		0.27		0.14		0.11

Table A2 Results of NF Model versus design codes for Fastened - Interior Two Flange Loading (ITF)

-----Exceeds Eurocode Limit

									EUROCODE		**NAS 2004**		**NF**	
No	Specimen	t (mm)	Fy MPa	H	R	N	θ (0)	Pt (kN) TEST	Pn (kN)	Pt/Pn	Pn (kN)	Pt/Pn	Pn (kN)	Pt/Pn
1	10W-ITF	0.61	265	80.1	3.91	41.7	70	1.56	1.42	1.1	1.4	1.11	1.41	1.11
2	11W-ITF	0.965	274	50.1	2.47	26.3	70	3.07	3.29	0.93	3.54	0.87	2.98	1.03
3	**12W-ITF**	**1.524**	**231**	**32.5**	**1.56**	**16.7**	**70**	**6.14**	**6.88**	**0.89**	**7.15**	**0.86**	**7.89**	**0.78**
4	13W-ITF	0.61	265	168	3.91	41.7	70	1.16	1.42	0.82	1.26	0.92	1.03	1.12
5	14W-ITF	0.965	274	107	2.47	26.3	70	3.12	3.29	0.95	3.27	0.95	2.75	1.13
6	15W-ITF	1.524	231	67.2	1.56	16.7	70	6.81	6.88	0.99	6.74	1.01	7.25	0.94
7	16W-ITF	0.61	265	98.4	3.91	41.7	50	1.38	1.28	1.08	1.12	1.24	1.19	1.16
8	**17W-ITF**	**0.965**	**274**	**64.3**	**2.47**	**26.3**	**50**	**3.16**	**2.96**	**1.07**	**2.82**	**1.12**	**2.52**	**1.25**
9	18W-ITF	1.524	231	40.5	1.56	16.7	50	6.05	6.2	0.98	5.74	1.06	6.02	1.01
10	19W-ITF	0.61	265	207	3.91	41.7	50	0.89	------	------	0.99	0.9	0.93	0.96
11	20W-ITF	0.965	274	132	2.47	26.3	50	2.45	2.96	0.83	2.59	0.95	2.14	1.14
12	21W-ITF	1.524	231	85.4	1.56	16.7	50	5.74	6.2	0.93	5.36	1.07	5.45	1.05

13	**31W-ITF**	**0.61**	**265**	**156**	**3.91**	**41.7**	**90**	**1.25**	**1.61**	**0.78**	**1.36**	**0.91**	**1.12**	**1.11**
14	32W-ITF	0.965	274	98	2.47	26.3	90	2.76	3.72	0.74	3.52	0.78	3.24	0.85
15	33W-ITF	1.524	231	62	1.56	16.7	90	9.21	7.78	1.18	7.23	1.27	8.94	1.03
16	10WR-ITF	0.627	318	152	7.59	81	70	1.78	1.86	0.96	1.78	1	1.92	0.93
17	14WR-ITF	1.003	299	91.1	6.33	50.6	70	4.05	4.05	1	4.13	0.98	3.54	1.14
18	**15WR-ITF**	**1.539**	**302**	**60.2**	**4.13**	**33**	**70**	**8.99**	**8.89**	**1.01**	**9.72**	**0.93**	**6.98**	**1.29**
19	17WR-ITF	1.003	299	88.2	8.71	50.6	70	3.43	3.81	0.9	3.87	0.89	3.46	0.99
20	18WR-ITF	1.539	302	52.5	7.23	33	70	8.55	8.16	1.05	8.92	0.96	8.4	1.02
21	3U-ITF	0.813	291	39	4.88	46.9	70	2.8	2.66	1.05	2.92	0.96	3.03	0.93
22	4U-ITF	0.813	291	39	4.88	62.5	70	3.38	2.94	1.15	3.19	1.06	3.39	1
23	**5U-ITF**	**0.813**	**291**	**39**	**4.88**	**46.9**	**70**	**3.07**	**2.66**	**1.15**	**2.92**	**1.05**	**3.03**	**1.01**
24	6U-ITF	0.813	291	39	4.88	62.5	70	3.69	2.94	1.26	3.19	1.16	3.39	1.09
25	9U-ITF	0.813	291	39	4.88	46.9	70	3.12	2.66	1.17	2.92	1.07	3.03	1.03
26	10U-ITF	0.813	291	39	4.88	62.5	70	3.38	2.94	1.15	3.19	1.06	3.39	1
27	1C-ITF	0.914	286	76.4	3.47	41.7	81.5	3.96	3.6	1.1	3.65	1.08	3.35	1.18
28	**2C-ITF**	**0.914**	**286**	**76.4**	**3.47**	**55.6**	**81.5**	**4.23**	**3.96**	**1.07**	**3.98**	**1.06**	**3.73**	**1.13**
29	3C-ITF	0.914	286	76.4	3.47	83.3	81.5	4.67	4.56	1.02	4.52	1.03	4.49	1.04
30	4C-ITF	0.914	286	76.4	3.47	111	81.5	5.56	5.06	1.1	4.98	1.12	5.24	1.06
31	5C-ITF	0.813	282	85.9	3.91	46.9	81.5	2.94	2.89	1.02	2.86	1.03	2.74	1.07
32	6C-ITF	0.813	282	85.9	3.91	62.5	81.5	2.94	3.19	0.92	3.12	0.94	2.97	0.99
33	**7C-ITF**	**0.813**	**282**	**85.9**	**3.91**	**93.8**	**81.5**	**3.56**	**3.69**	**0.97**	**3.56**	**1**	**3.44**	**1.04**
34	8C-ITF	0.813	282	85.9	3.91	125	81.5	3.78	4.1	0.92	3.93	0.96	3.9	0.97

35	1R-ITF	1.245	333	23.3	5.1	30.6	77.5	7.61	6.06	1.26	7.4	1.03	7.76	0.98
36	2R-ITF	1.245	333	23.3	5.1	40.8	77.5	8.19	6.64	1.23	8.01	1.02	8.13	1.01
37	3R-ITF	1.245	333	23.3	5.1	61.2	77.5	8.9	7.6	1.17	9.05	0.98	8.88	1
38	**4R-ITF**	**0.635**	**304**	**49.2**	**10**	**60**	**77.5**	**2.05**	**1.66**	**1.24**	**1.76**	**1.16**	**2.55**	**0.8**
39	5R-ITF	0.635	304	49.2	10	80	77.5	2.23	1.83	1.22	1.93	1.15	2.39	0.93
40	6R-ITF	0.635	304	49.2	10	120	77.5	2.23	2.13	1.05	2.22	1	2.08	1.07
41	7R-ITF	1.245	338	20.6	5.1	30.6	66.5	6.32	5.73	1.1	7.09	0.89	6.88	0.92
42	8R-ITF	1.245	338	20.6	5.1	40.8	66.5	7.79	6.27	1.24	7.67	1.02	7.25	1.07
43	**9R-ITF**	**1.245**	**338**	**20.6**	**5.1**	**61.2**	**66.5**	**8.77**	**7.18**	**1.22**	**8.66**	**1.01**	**7.99**	**1.1**
44	10R-ITF	0.66	335	38.8	9.62	57.7	66.5	2.72	1.75	1.55	2.01	1.35	2.3	1.18
45	11R-ITF	0.66	335	38.8	9.62	76.9	66.5	2.67	1.94	1.38	2.2	1.21	2.83	0.95
46	13R-ITF	1.194	284	47.1	1.33	31.9	45	4.67	5.03	0.93	4.72	0.99	4.75	0.98
47	14R-ITF	1.194	284	47.1	1.33	42.6	45	5.21	5.51	0.95	5.11	1.02	4.84	1.08
48	**15R-ITF**	**1.194**	**284**	**47.1**	**1.33**	**63.8**	**45**	**6.01**	**6.31**	**0.95**	**5.78**	**1.04**	**5.02**	**1.2**
49	16R-ITF	0.635	336	91	2.5	60	45	1.56	1.81	0.86	1.68	0.93	1.45	1.07
50	17R-ITF	0.635	336	91	2.5	80	45	1.69	2	0.84	1.84	0.92	1.62	1.04
51	18R-ITF	0.635	336	91	2.5	120	45	1.87	2.32	0.81	2.11	0.88	1.95	0.96
52	25R-ITF	1.27	291	51.7	3.13	30	87.5	6.28	6.64	0.95	6.96	0.9	5.97	1.05
53	**26R-ITF**	**1.27**	**291**	**51.7**	**3.13**	**40**	**87.5**	**6.63**	**7.26**	**0.91**	**7.54**	**0.88**	**6.32**	**1.05**
54	27R-ITF	1.27	291	51.7	3.13	60	87.5	7.3	8.31	0.88	8.51	0.86	7.03	1.04
55	28R-ITF	0.813	307	82.1	4.88	46.9	87.5	2.94	3.05	0.96	3.06	0.96	2.74	1.07
56	29R-ITF	0.813	307	82.1	4.88	62.5	87.5	3.12	3.36	0.93	3.34	0.93	2.97	1.05

57	30R-ITF	0.813	307	82.1	4.88	93.8	87.5	3.29	3.88	0.85	3.8	0.87	3.42	0.96
								Mean		**1.03**		**1.01**		**1.04**
								StdDev		**0.16**		**0.11**		**0.10**
								C.O.V		**0.15**		**0.11**		**0.09**

Table A3 Results of NF Model versus design codes for Fastened - Interior One Flange Loading (IOF)

-----Exceeds Eurocode Limit

									EUROCODE		**NAS 2004**		**NF**	
No	Specimen	t (mm)	Fy MPa	H	R	N	θ (0)	Pt (kN) TEST	Pn (kN)	Pt/Pn	Pn (kN)	Pt/Pn	Pn (kN)	Pt/Pn
1	**14W-IOF**	**0.965**	**274**	**98**	**2.47**	**26.3**	**70**	**2.51**	**2.56**	**0.98**	**2.91**	**0.86**	**2.95**	**0.85**
2	15W-IOF	0.61	265	158	3.91	41.7	70	0.92	1.08	0.85	1.18	0.78	1.13	0.81
3	16W-IOF	1.524	231	129	1.56	16.7	70	6.4	5.50	1.16	5.7	1.12	6.39	1.00
4	17W-IOF	0.965	274	204	2.47	26.3	70	2.81	2.56	1.10	2.86	0.99	2.50	1.12
5	23W-IOF	0.991	274	97	2.41	25.6	50	2.11	2.43	0.87	2.49	0.85	2.56	0.82
6	**24W-IOF**	**0.635**	**265**	**153**	**3.75**	**40**	**50**	**0.98**	**1.05**	**0.94**	**1.04**	**0.94**	**1.12**	**0.87**
7	25W-IOF	1.549	231	126	1.54	16.4	50	5.34	5.11	1.04	4.79	1.11	5.39	0.99
8	26W-IOF	1.016	274	194	2.35	25	50	2	-----	-----	2.56	0.78	1.93	1.04
9	51W-IOF	0.914	274	108	2.61	27.8	70	2.38	2.32	1.03	2.63	0.91	2.65	0.90
10	52W-IOF	0.61	265	165	3.91	41.7	70	1.15	1.08	1.07	1.18	0.98	1.10	1.04
11	**54W-IOF**	**0.914**	**274**	**135**	**2.61**	**27.8**	**50**	**1.88**	**2.09**	**0.90**	**2.13**	**0.88**	**2.10**	**0.90**

12	55W-IOF	0.965	274	128	2.47	26.3	50	1.95	2.31	0.84	2.36	0.83	2.28	0.86
13	56W-IOF	0.914	274	136	2.61	27.8	50	1.89	2.09	0.90	2.13	0.89	2.09	0.90
14	89W-IOF	0.61	265	168	3.91	41.7	70	1.11	1.08	1.03	1.18	0.94	1.09	1.02
15	91W-IOF	0.965	274	107	2.47	26.3	70	2.56	2.56	1.00	2.9	0.88	2.91	0.88
16	**101W-IOF**	**0.61**	**265**	**207**	**3.91**	**41.7**	**50**	**0.84**	**-----**	**-----**	**0.96**	**0.87**	**0.98**	**0.86**
17	103W-IOF	0.965	274	132	2.47	26.3	50	2.34	2.31	1.01	2.36	0.99	2.26	1.04
18	139W-IOF	0.508	265	189	4.5	50	90	1.07	0.87	1.23	0.9	1.19	1.10	0.97
19	30WR-IOF	0.627	318	152	7.59	81	70	1.47	1.12	1.32	1.64	0.9	1.21	1.22
20	33WR-IOF	0.848	284	110	5.61	59.9	70	2.25	1.88	1.20	2.6	0.87	2.49	0.90
21	**39WR-IOF**	**0.627**	**318**	**148**	**10.1**	**81**	**70**	**1.58**	**1.05**	**1.50**	**1.54**	**1.03**	**0.95**	**1.66**
22	42WR-IOF	1.003	299	91.1	6.33	50.6	70	3.21	2.55	1.26	3.6	0.89	3.37	0.95
23	48WR-IOF	0.549	278	166	13	92.6	70	1.18	0.73	1.61	1.01	1.17	1.14	1.03
24	51WR-IOF	1.003	299	88.2	8.71	50.6	70	3.11	2.40	1.30	3.39	0.92	3.12	1.00
25	57WR-IOF	0.627	318	191	7.59	81	50	1.46	-----	-----	1.33	1.1	1.45	1.01
26	**60WR-IOF**	**0.848**	**284**	**130**	**8.42**	**59.9**	**50**	**2.11**	**1.58**	**1.34**	**1.96**	**1.08**	**1.61**	**1.31**
27	66WR-IOF	0.627	318	192	10.1	81	50	1.33	-----	-----	1.25	1.07	1.34	1.00
28	69WR-IOF	1.003	299	113	6.33	50.6	50	3.08	2.29	1.34	2.92	1.05	2.66	1.16
29	75WR-IOF	0.549	278	200	13	92.6	50	1	-----	-----	0.82	1.23	1.00	1.00
30	78WR-IOF	1.003	299	114	9.49	50.6	50	2.98	2.12	1.40	2.7	1.11	3.12	0.95
31	**81WR-IOF**	**1.539**	**302**	**72.3**	**6.19**	**33**	**50**	**6.61**	**4.95**	**1.33**	**6.28**	**1.05**	**5.10**	**1.30**
32	137WR-IOF	0.627	318	152	7.59	162	70	1.91	1.12	1.71	2.05	0.94	1.87	1.02
33	140WR-IOF	0.627	318	148	10.1	162	70	1.91	1.05	1.82	1.93	0.99	1.97	0.97

34	144WR-IOF	1.003	299	88.2	8.71	101	70	3.78	2.40	1.58	4.16	0.91	3.74	1.01
35	FD7-F	0.66	396	103	6.62	202	71	3.51	1.41	2.50	3.19	1.1	3.39	1.04
36	**FD8-F**	**0.66**	**396**	**103**	**6.62**	**202**	**71**	**3.47**	**1.41**	**2.47**	**3.18**	**1.09**	**3.39**	**1.02**
37	FD5	0.66	396	103	6.62	202	71	3.29	1.41	2.34	2.99	1.1	3.39	0.97
38	FD6	0.66	396	103	6.62	202	71	3.37	1.41	2.40	3.09	1.09	3.39	1.00
								Mean		**1.34**		**1.02**		**1.01**
								StdDev		**0.48**		**0.13**		**0.16**
								C.O.V		**0.36**		**0.12**		**0.15**

Table A4 Results of NF Model versus design codes for Unfastened - End One Flange Loading (EOF)

-----Exceeds Eurocode Limit

* Based on Fy = 360 MPa

** Based on Fy = 413.7 MPa

									EUROCODE		**NAS 2004**		**NF**	
No	Specimen	t (mm)	Fy MPa	H	R	N	θ (0)	Pt (kN) TEST	Pn (kN)	Pt/Pn	Pn (kN)	Pt/Pn	Pn (kN)	Pt/Pn
1	EOF-1A	0.742	298	62.7	6.85	102	62.4	2.12	1.34	1.58	1.47	1.44	2.33	0.91
2	EOF-1B	0.744	298	62.1	6.83	102	61.6	2.14	1.34	1.59	1.47	1.45	2.34	0.91
3	**EOF-2A**	**0.765**	**298**	**59.5**	**6.98**	**197**	**62.1**	**2.62**	**1.83**	**1.43**	**2.01**	**1.31**	**2.46**	**1.07**
4	EOF-2B	0.752	298	61.1	7.1	200	62.7	2.57	1.78	1.45	1.95	1.32	2.41	1.07
5	EOF-3A	1.123	296	40.3	4.53	67.4	63.7	5.29	2.83	1.87	3.14	1.68	4.89	1.08
6	EOF-3B	1.135	296	39.8	4.47	66.7	63	5.35	2.87	1.86	3.19	1.68	4.87	1.10
7	EOF-4A	1.199	296	38.1	4.45	126	64.4	5.54	4.08	1.36	4.52	1.22	5.86	0.95
8	**EOF-4B**	**1.196**	**296**	**38**	**4.46**	**126**	**64.5**	**5.45**	**4.06**	**1.34**	**4.51**	**1.21**	**5.86**	**0.93**
9	EOF-5A	0.79	331	88.7	6.43	95.8	69.5	1.77	1.64	1.08	1.83	0.97	2.13	0.83
10	EOF-5B	0.805	331	87.4	6.31	94	70	1.82	1.71	1.07	1.90	0.96	2.30	0.79
11	EOF-6A	0.744	331	92.2	6.83	202	70.5	2.7	1.93	1.40	2.14	1.26	2.66	1.01

12	EOF-6B	0.747	331	93.5	6.8	202	70	2.7	1.95	1.39	2.15	1.26	2.62	1.03
13	**EOF-7A**	**1.24**	**284**	**55.7**	**3.89**	**61.1**	**71.3**	**4.46**	**3.48**	**1.28**	**3.66**	**1.22**	**6.06**	**0.74**
14	EOF-7B	1.217	284	57.2	3.97	62.2	72.2	4.46	3.38	1.32	3.55	1.26	6.07	0.73
15	EOF-8A	1.168	284	58	4.57	129	71.3	6.38	3.96	1.61	4.17	1.53	5.90	1.08
16	EOF-8B	1.219	284	54.8	4.38	124	71.3	6.26	4.27	1.46	4.52	1.39	6.35	0.99
17	EOF-19A	0.732	284	57.6	4.86	103	75.9	1.46	1.46	1.00	1.54	0.95	1.73	0.85
18	**EOF-19B**	**0.729**	**284**	**56.4**	**4.88**	**104**	**75.1**	**1.35**	**1.44**	**0.94**	**1.53**	**0.88**	**1.67**	**0.81**
19	FD1	0.66	396	103	6.62	101	71	1.51	1.28	1.18	1.53	0.98	1.48	1.02
20	FD2	0.66	396	103	6.62	101	71	1.48	1.28	1.15	1.53	0.96	1.48	1.00
21	t26h0.75R3/32	0.432	775	45.3	5.47	58.8	61	0.73	0.62	1.18	1.11	0.66	0.73	1.00
22	t26h0.75R3/64	0.432	775	45.3	2.77	58.8	61	0.76	0.67	1.13	1.15	0.66	0.75	1.02
23	**t26h1.5R3/32**	**0.432**	**775**	**88.8**	**2.77**	**58.8**	**60.1**	**0.54**	**-----**	**-----**	**1.02**	**0.48**	**1.17**	**0.46**
24	t26h1.5R3/64	0.432	775	90	5.47	58.8	61	0.49	-----	-----	1.04	0.52	0.48	1.01
25	t22h0.75R5/64	0.737	716	27.9	2.69	34.5	60.4	2.08	1.58	1.31	2.71	0.77	1.97	1.06
26	t22h0.75R1/16	0.737	716	25.9	2.17	34.5	60.6	2.16	1.62	1.34	2.75	0.79	2.02	1.07
27	t22h1.5R5/64	0.737	716	53.4	2.69	34.5	59.8	1.83	1.58	1.16	2.53	0.72	1.85	0.99
28	**t22h1.5R1/16**	**0.737**	**716**	**52.1**	**2.17**	**34.5**	**60**	**2.07**	**1.61**	**1.28**	**2.56**	**0.81**	**1.83**	**1.13**
29	t22h2R5/64	0.737	716	70.7	2.69	34.5	61	1.4	1.59	0.88	2.48	0.56	1.84	0.76
30	t22h2R1/16	0.737	716	69	2.17	34.5	59.9	1.45	1.61	0.90	2.48	0.59	1.77	0.82
31	t22h3R5/64	0.737	716	106	2.69	34.5	60.4	1.92	1.58	1.21	2.32	0.83	1.70	1.13
32	t22h3R1/16	0.737	716	103	2.17	34.5	60.5	2.07	1.62	1.28	2.35	0.88	1.75	1.18
33	**t22h4.5R5/64**	**0.737**	**716**	**157**	**2.69**	**34.5**	**61.6**	**1.5**	**-----**	**-----**	**2.17**	**0.69**	**1.50**	**1.00**

34	t22h4.5R1/16	0.737	716	156	2.17	34.5	61	1.64	-----	-----	2.17	0.75	1.62	1.01
35	t22h6R5/64	0.737	716	208	2.69	34.5	62.8	1.23	-----	-----	2.04	0.60	1.20	1.02
36	t22h6R1/16	0.737	716	207	2.17	34.5	61	1.33	-----	-----	2.02	0.66	1.43	0.93
								Mean:		**1.3**		**1**		**0.96**
								StdDev:		**0.25**		**0.34**		**0.14**
								C.O.V:		**0.19**		**0.34**		**0.15**