International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 4 Issue 12, December-2015

A Novel Design Procedure for Optimal Design of CFS Compression Members

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***Abstract*—This paper presents a novel design procedure for optimal design of lipped channel CFS[a] compression members under simply supported condition. The design is based on Effective Width Method (EWM) as specified in AISI S 100 2013 (North American Specification for the design of Cold-Formed Steel Structural Members). The length of the compression member is taken as 1200 mm and the sections dimension parameters are varied for web depth (d_w[b]) 50-210 mm, flange (b_F[c]) from 25-50 mm and lip length (b_L[d]) can be chosen from 0.4 - 0.6 times the width of the flange. The methodology adopted in this paper for the design is firstly to develop a MATLAB coding based on the column strength curve of EWM for various buckling failures like local, distortional, global and local+global interaction mode. Then, the failure loads and stresses obtained from the MATLAB coding is analysed to interpret the dependence between failure load, stresses and the geometrical properties of the section. Based on the interpretation made an easy and optimal design procedure is been proposed, also the results obtained from this novel design procedure is validated through Direct Strength Method (DSM).**

***Index Terms*— [a]CFS, [b]web depth, [c]flange width, [d]lip length, [e]buckling failures.**

I. INTRODUCTION

Cold formed sections are generally thinner and also have mode of failures and deformation which are not usually encountered in normal Hot Rolled Steel sections design. Further cold form steel production process produces structural buckling imperfections which are different from hot rolled and welded members. Cold formed steel is preferred over Hot rolled steel because of lightness, high strength, non-shrinkage, accuracy in detailing, stiffness properties at ambient temperature. AISI S 100 2013 (North American Specification for the design of Cold-Formed Steel Structural Members 2013 Edition) is used as the design procedure of CFS members. It specifies the design for finding the load capacity of the section when subjected to buckling failures. The advantages of using cold-formed steel sections are high strength-to-weight ratio, easy fabrication into different cross-section shapes, easy for construction purposes, etc. Cold-formed steel sections are manufactured into different types like lipped channel sections, channel sections, Z-sections, etc by cold-rolling or brake-pressing technique. The plate elements constituting the cold-formed steel sections usually have large width-to-thickness ratio. Hence, local buckling and distortional buckling are usually the governing modes of failure for cold-formed steel
members. Many investigations have been done on cold-formed steel sections and design rules can be found in the specifications of countries, such as the European Code, North American Specification and Indian Standard. There are two main design methods, namely the effective width method (EWM) and the direct strength method (DSM) that are generally used to calculate failures of different members failed by local buckling, distortional buckling and global buckling. However, when sections were stiffened by edge and intermediate stiffeners for optimization of section, the calculation of effective width for each plate element could be quite tedious that involves various iteration and the EWM becomes much more complicated compared to the DSM.

II. BACKGROUND

Effective width method deals with calculation of local buckling, distortional buckling and global buckling of individual element of the section. AISI S-100 2013 provides a design to find out the load capacity for different lipped channel section. But finding the optimal section for a given load capacity is still lacking. Hence, our work focusses on finding the optimal section for a given load capacity by providing a design of optimal section. The effective width method provided in AISI S-100 involves laborious calculations to find the load capacity of the section and to avoid this a MATLAB programming code is developed which will be helpful in calculating the ultimate strength of the section within a short duration.
The range of Web, flange and Lip depth and their corresponding thickness as analysed in the project is as shown in Table 1.According to American Standard Code AISI S100 2013 the width to Thickness considerations for different parts of lip channel section of web, flange and lip is given in equations (1) (2) and (3) respectively.

For Web $d_w/t \leq 500$ (1)

For Flange $b_F/t \leq 60$ (2)

For Lip $b_L/t \leq 60$ (3)

Where, t = thickness of element

d_w = width of respective element

Table 1: Technical specifications of the cross sections analysed

	Range (mm)	Increment of (mm)
Web	50 – 210	10
Flange	25 – 50	2.5
Lip	10 – 20	1
Thickness	1 – 4	0.5

III. GRAPHICAL ANALYSYS

The figure 1 is stress v/s (thickness/web length) (t/d_w) for Length of compression member (L) =1200 and different thicknesses. It can be clearly seen that for least web we get maximum permissible stress for constant flange and lip. And with the increase in web length, the value of permissible stress decreases.

The figure 2 corresponds to Length of compression member (L) = 1200 mm and thickness (t) =1mm .With the increase in value of r the permissible stress also increases. Each curve corresponds to a different web as shown. The topmost curve corresponds to web (d_w) = 50mm and lowermost corresponds to web (d_w)=190. As the curves are smooth, we can easily interpolate the values of stress corresponding to different values of radius of gyration. There will be different graphs for different lengths and thicknesses. Therefore tables are provided for the convenience. The table for the above graph is given below (interpolated values). (Ref. Table 4)

It can be seen from the graph that as the value of r increases the (d_w/b_F) ratio decreases. Each curve corresponds to a particular web as shown. Because the curves are smooth the intermediate values can be interpolated.

As the radius of gyration and (d_w/b_F) ratio are independent of length. This graph will be same for all the lengths. But as the thickness changes the value of radius of gyration changes but (d_w/b_F) ratio remains same. From observation of various data as shown below, it can be said that value of r increases by 0.01 mm if thickness is increased by 1mm. thus r value for different thickness can be calculated once we know r value for thickness = 1mm.Therefore the above graph will serve for all the lengths and thicknesses. (Ref. Table 3)

IV. PROPOSED DESIGN PROCEDURE FOR OPTIMAL DESIGN

Graphs between Stress v/s r (radius of gyration) and (d_w/b_f) ratio v/s r (radius of gyration) were plotted for constant web and lip lengths.

As web length and lip length are kept constant, therefore area of the section increases as r increases.

Following are the observations from the graphs:

a. Permissible stress increases as the value of r increases.
b. (d_w/b_f) ratio decreases as the value of r increases.

Thus for economic section, r value should be less or (d_w/b_f) ratio should be more and for section to have more permissible stress (safe section), r value should be more or (d_w/b_f) ratio should be less for a given range of (d_w/b_f) ratio. The minimum value corresponds to the safest section and the maximum value corresponds to the most economical section for a constant web.

i.e. if $a \leq (d_w/b_f) \leq b$ for a constant web then

At (d_w/b_f) = a the section will have maximum permissible stress (safe section)

And at (d_w/b_f) = b the section will have least area (most economical section)

A. Steps to be followed in Design for Most Economical Section:

Step 1: Choose thickness for given load from table 2 and take web d_w = 50 mm (as it has maximum permissible stress)
Step 2:From (d_w/b_f) v/s r graph, take minimum value of (d_w/b_f) for the same web and get the corresponding value of r.
Step 3:Use this (d_w/b_f) ratio and find the length of flange.
Step 3:Calculate the area and find out the actual stress.
Step 3:Use the table to find the permissible stress value with the help of r and thickness t value.
Step 3:Compare the actual stress and permissible stress.

Case a: If Actual stress > Permissible stress, choose next web length and repeat the procedure till the permissible stress exceeds actual stress.

Case b: If Permissible stress > Actual stress, then the chosen section is safe but may not be most economical.

Now take greater values of (d_w/b_f) ratio without changing web and find out the actual and permissible stress. Keep increasing the ratio until actual stress value approaches the permissible stress. The maximum value of (d_w/b_f) ratio at which permissible stress is greater than actual stress will correspond to the most economical section.

The above procedure will help in selecting the web length and flange length for a given lip length (b_L) (i.e 10 mm). From the graphs between stress v/s lip length (b_L), it can be concluded that permissible stress increases slightly on increasing lip length. But to avoid distortional buckling, lip to flange ratio should be between 0.4 to 0.6 as this range gives maximum value of permissible distortional stress as shown by the graph.

The Figure 4 between distortional stress v/s (bl/bf) ratio, for constant web length and different flange lengths, clearly shows that for all the flange lengths the maximum distortional permissible stress corresponds to 0.4 to 0.6 (b_l/b_f) ratio.

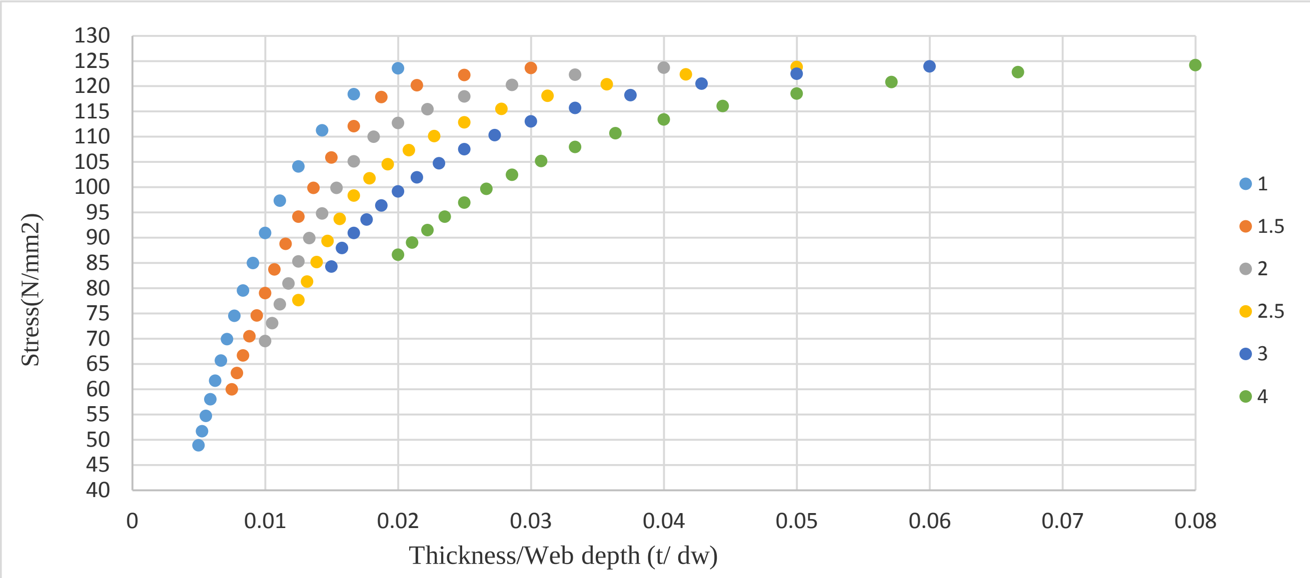


Figure 1: Stress v/s (thickness/web length) (t/ d_w) L=1200

Figure 2: Stress v/s r graph

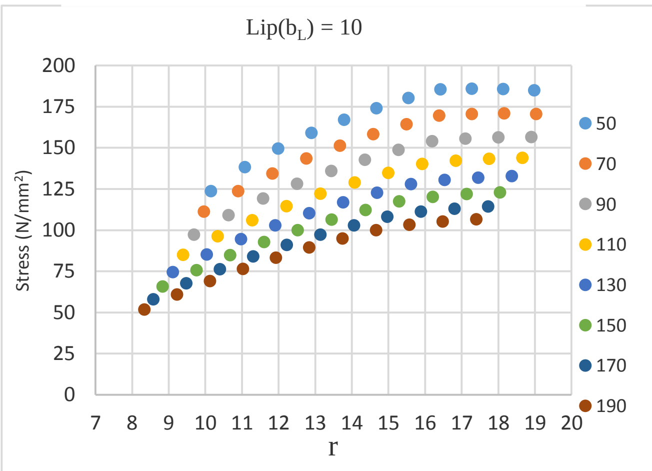


Figure 3: (d_w/b_F) v/s r

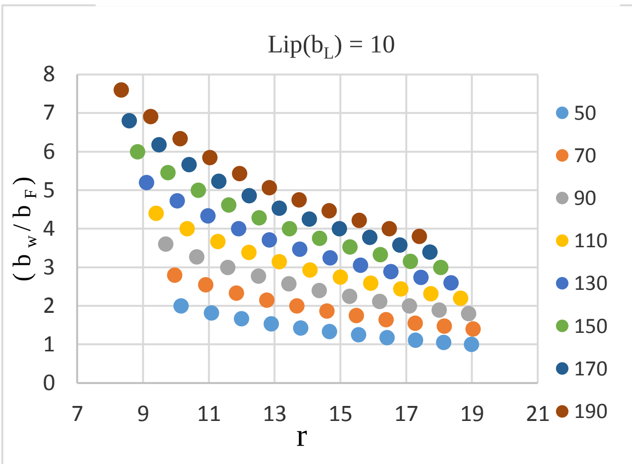
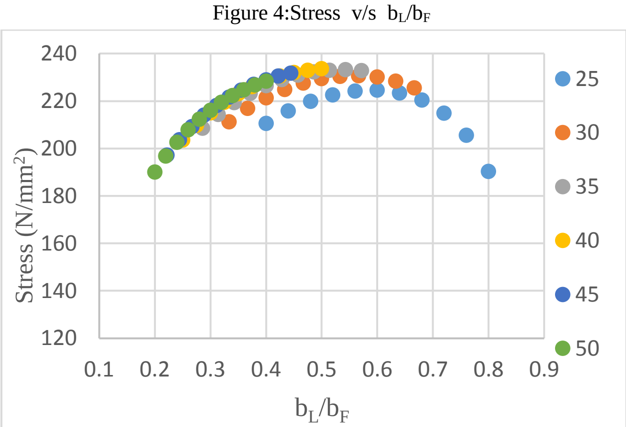


Figure 4:Stress v/s b_L/b_F



V. EXAMPLE CALCULATION PROCEDURE FOR OPTIMAL SECTION

Design of Lip Channel Compression Member of Length = 1200 mm for given load of 50 kN.

From Table.2 select a thickness = 2 mm.

Trial 1: Take web = 50 mm.

From fig.3 $1 \leq d_w/b_F \leq 2$ for web = 50 mm.

Taking d_w/b_F = 1.1 for section to be safe. Therefore, b_f = 45.45 mm.

For thickness = 1mm corresponding value of r = 17.3 mm for d_w/b_F = 1.1. (From fig.3)

Therefore, for thickness = 2mm r = 17.3 +0.01 = 17.31 mm.

From table.4 for web = 50 mm and thickness = 2 mm, Permissible stress = 195.71 N/mm^2 for r = 17.31 mm (By interpolation)

Actual stress = Load/Area

= 50000/ [(50+ (2*45.45) + (2*10))*2] = 155.37 N/mm^2.

Hence, the section is safe but may not be economical.

For economical section increase d_w/b_f to 1.3. Therefore, bf = 38.46 mm.

For thickness = 1mm corresponding value of r = 14.99 mm for d_w/b_F = 1.3. (From fig.3)

Therefore, for thickness = 2mm r = 14.99 +0.01 = 15 mm.

From table.4 for web = 50 mm and thickness = 2 mm,

Permissible stress = 180 N/mm^2 for r = 15 mm (By interpolation)

Actual stress = Load/Area.

= 50000/[(50+(2*38.46.45)+(2*10))*2] = 170.16 N/mm^2.

As, the difference between actual and permissible stress is less, hence the section is safe and economical.

To avoid distortional buckling take lip = 0.4 times b_F = 15.58mm.

The optimised section is d_w , b_f , b_L , = 50 mm , 38 mm , 16 mm respectively.

VI. VALIDATION OF RESULTS BY DIRECT STRENGTH METHOD (DSM):

Web = 50 mm , Flange = 38 mm , Lip = 16 mm , Thickness = 2 mm , A_g = 316 mm^2.

Load capacity for flexural – torsional buckling:

$P_{cre}/P_y = 2.0909$

$\lambda_c^2 = P_y/ P_{cre} = 0.6915$

$P_Y = (250 * A_g)/1000 = 79$ kN

$P_{ne} = 0.658^{\lambda_c^2} = 64.66$ kN.

Load capacity for Local Buckling:

$P_{crl}/P_y = 5.9747$

$P_{crl} = (0.66* P_Y)/1000 = 52.14$

$\lambda_l = P_{crl}/P_{ne} =$

$$P_{nl} = \left[1 - 0.15\left(\frac{P_{crl}}{P_{ne}}\right)^{0.4}\right]\left(\frac{P_{crl}}{P_{ne}}\right)^{0.4} P_{ne} \quad = 51.16 \text{ kN.}$$

Load capacity for distortional buckling:

$P_{crd}/P_y = 4.0368$

$$\lambda_d = \sqrt{\frac{P_Y}{P_{crd}}} = 0.4977$$

$$P_{nd} = \left(1 - 0.22\left(\frac{P_{crd}}{P_y}\right)^{0.5}\right)\left(\frac{P_{crd}}{P_y}\right)^{0.5} P_Y = 77.1\ kN$$

Load capacity of the section = min(P_{ne} , P_{nl} , P_{nd}) = 51.16 kN

Hence, the load capacity is approximately same as given for the design. Thus, the result is validated by Direct Strength Method (DSM).

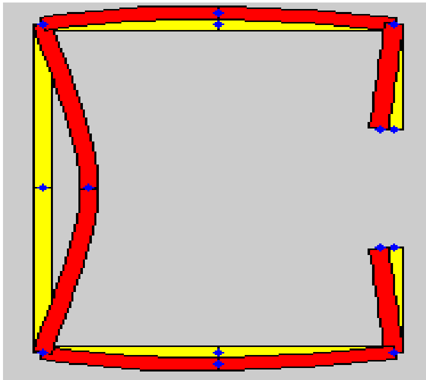


Figure 5: Local Buckling
Length = 40, Load Factor = 5.964

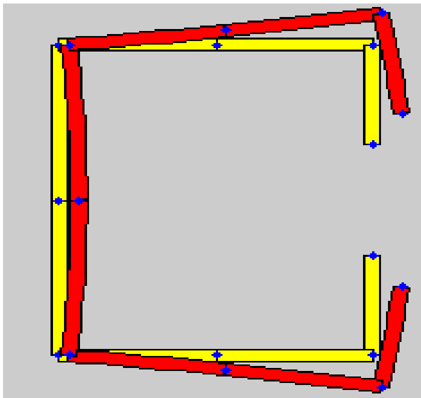


Figure 6: Distortional Buckling
Length = 350, Load Factor = 4.093

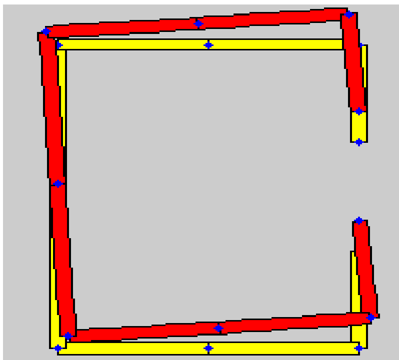


Figure 7: Global Buckling
Length = 350, Load Factor = 3.618

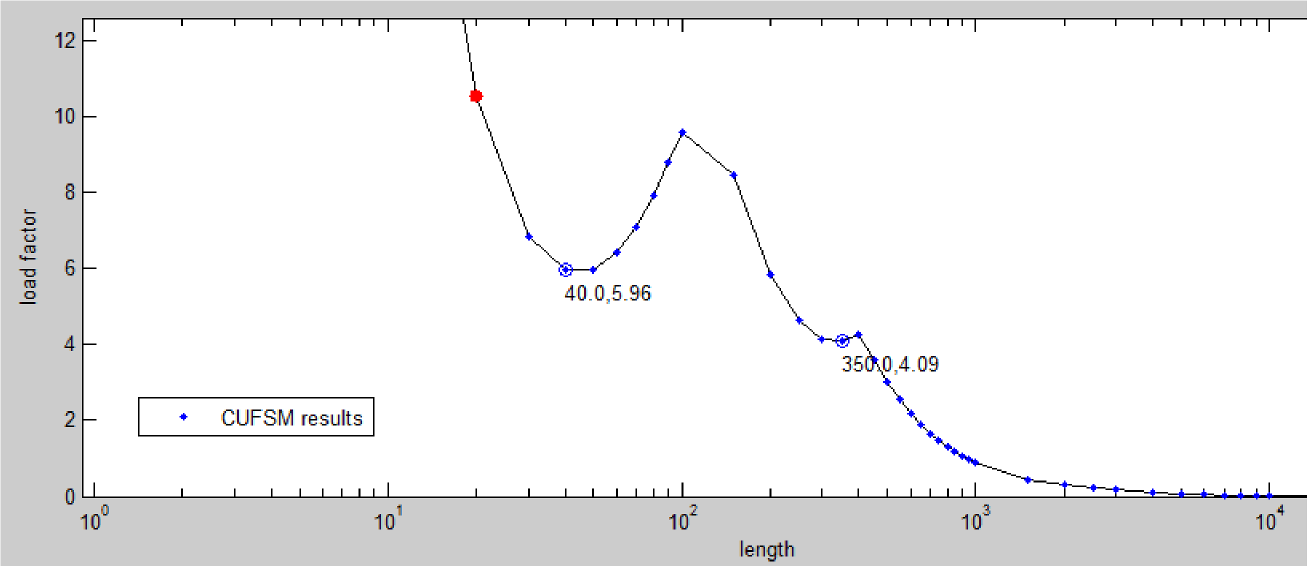


Figure 8: CUFSM graph for different buckling failures

VII. CONCLUSION

The numerical investigation on the cold-formed steel lipped channel sections subjected to axial compression have been presented. The method is inferred from all the graphs which gives the optimized section for a given loading condition. The section obtained will be safe against all the three conditions of failure i.e local-global interaction or separate local buckling and global buckling and distortional buckling cases. Thus it is recommended to use the design procedure for selection of the lipped channel cold form steel section so as to have the section to be most economical and safe.

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APPENDIX

Table 2. Maximum and Minimum load capacity for a given thickness

L=1200 mm		
	Minimum value (kN)	Maximum value (kN)
t=1	13.18	33.18
t=1.5	22.25	60.00
t=2	29.68	89.07
t=2.5	37.13	121.88
t=3	44.59	157.68
t=3.5	52.08	195.82
t=4	59.59	235.68

Table 3: Maximum and minimum value of radius of gyration

Radius of Gyration (r)								
t / d_w	1		2		3		4	
	min	max	min	max	min	max	min	Max
50	10.15	18.98	10.16	18.98	10.17	18.99	10.19	18.99
70	9.95	19.03	9.96	19.04	9.97	19.04	9.99	19.05
90	9.68	18.89	9.69	18.9	9.71	18.9	9.73	18.91
110	9.39	18.65	9.4	18.66	9.42	18.66	9.44	18.67
130	9.11	18.36	9.12	18.37	9.13	18.37	9.16	18.38
150	8.83	18.05	8.84	18.05	8.86	18.06	8.89	18.07
170	8.57	17.72	8.58	17.73	8.6	17.73	8.63	17.74
190	8.33	17.39	8.34	17.4	8.36	17.41	8.39	17.42

Table 4: Maximum permissible stress for lipped channel section (L=1200 mm F_y = 250 N/mm^2)

	Thickness(t)	1	1.5	2	2.5	3	3.5	4
Web (d_w)	r							
50	8	–	–	–	–	–	–	–
	10	121.14	121.13	121.10	121.22	121.15	121.13	121.14
	12	149.49	150.89	150.90	150.90	150.89	150.88	150.88
	14	168.74	172.42	172.43	172.43	172.43	172.43	172.43
	16	182.86	188.10	188.10	188.10	188.10	188.10	188.10
	18	185.75	199.72	199.72	199.72	199.72	199.71	199.71
70	8	–	–	–	–	–	–	–
	10	111.77	120.79	120.80	120.81	120.82	120.83	120.84
	12	135.92	150.73	150.77	150.78	150.78	150.79	150.79
	14	153.77	170.68	172.39	172.39	172.39	172.39	172.39
	16	167.24	184.56	188.09	188.09	188.09	188.09	188.09
	18	170.81	194.94	199.71	199.71	199.71	199.71	199.71
90	8	–	–	–	–	–	–	–
	10	101.15	116.37	120.58	120.58	120.59	120.59	120.60
	12	123.28	140.84	150.67	150.67	150.67	150.68	150.68
	14	139.98	158.56	171.92	172.37	172.37	172.37	172.37
	16	152.88	171.72	185.79	188.12	188.12	188.12	188.12
	18	156.35	181.79	195.99	199.75	199.75	199.75	199.75
110	8	–	–	–	–	–	–	–
	10	92.11	107.84	119.20	120.56	120.56	120.55	120.55
	12	112.56	130.35	144.22	150.72	150.72	150.72	150.71
	14	128.26	146.94	161.92	172.47	172.47	172.46	172.46
	16	140.56	159.45	174.85	186.74	188.17	188.17	188.17
	18	143.47	169.16	184.61	196.72	199.70	199.70	199.70
130	8	–	–	–	–	–	–	–
	10	84.60	100.13	112.52	120.77	120.76	120.75	120.74
	12	103.54	120.91	135.30	146.72	150.83	150.84	150.85
	14	118.25	136.43	151.77	164.27	172.41	172.42	172.42
	16	128.99	148.37	164.09	177.09	187.39	188.09	188.09
	18	132.35	157.82	173.58	186.75	197.32	199.68	199.68
150	8	–	–	–	–	–	–	–
	10	78.05	93.03	105.55	115.61	120.64	120.64	120.65
	12	95.79	112.47	126.79	138.77	148.41	150.69	150.69
	14	109.76	127.21	142.41	155.37	166.08	172.37	172.37
	16	119.52	138.68	154.23	167.64	178.89	187.84	188.11
	18	122.80	147.85	163.45	176.99	188.46	197.87	199.73

170	8	51.94	63.33	72.93	80.34	81.99	81.18	81.34
	10	72.52	86.85	99.19	109.56	117.94	120.56	120.56
	12	89.26	105.18	119.20	131.31	141.54	149.68	150.72
	14	102.55	119.21	134.05	147.06	158.26	167.63	172.47
	16	111.40	130.17	145.34	158.76	170.43	180.35	188.12
	18	114.58	139.14	154.39	167.89	179.78	189.92	198.45
190	8	48.24	59.14	68.50	76.08	81.98	80.63	80.86
	10	67.83	81.52	93.56	103.98	112.76	119.61	120.67
	12	83.66	98.82	112.48	124.44	134.91	143.81	150.82
	14	96.24	112.10	126.63	139.29	150.62	160.45	168.77
	16	104.15	122.64	137.31	150.52	162.29	172.60	181.46
	18	–	–	–	–	–	–	–
210	8	79.68	102.08	121.79	139.57	155.91	170.67	184.19
	10	87.95	112.05	132.96	151.59	168.35	183.45	196.99
	12	94.25	119.55	141.28	160.44	177.47	192.62	205.99
	14	98.82	124.94	147.21	166.69	183.86	198.96	212.11
	16	101.89	128.55	151.15	170.81	188.03	203.07	216.02
	18	–	–	–	–	–	–	–