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Numerical investigation of thickness effect on the crack parameters

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ABSTRACT

In order to predict the fracture parameters correctly and efficiently, it is very important to look after the factors that affect the crack parameters. Specimen geometry is one such parameter which affects the parameters around the crack tip. This paper numerically investigates the effect of the thickness of the specimen on the crack parameters using the Finite Element Analysis tool 'ANSYS'. A side edge notched bend specimen was modeled and analyzed under three point bend condition for different specimen thickness. It was observed that with the increase in the thickness, the crack parameters around the crack tip decreases, and this increase in thickness leads to the shift of the state of stress from plane stress to plane strain.

1. INTRODUCTION

With the growing use of metal in day to day life, the chances of metal failure have also increased significantly. Due to the application of repeated loads, cracks generate in the material, which grows with time. The catastrophic failure of metals and structures induced the development of Fracture Mechanics. It deals with the initiation and propagation of crack and the factors that affect its initiation and growth. The theory of fracture mechanics was first given by Griffith [1] in 1921 which was underestimated until the pioneer work on the fracture of ductile material by Irwin [2, 3]. After which numerous researchers have worked decades for the development of fracture mechanics in order to make it a useful tool for designing materials and structures.

The engineering application of fracture mechanics requires appropriate parameters to quantify the crack tip condition. The crack tip condition is defined by many crack tip parameters being coined since the development of crack theories. Crack Mouth Opening Displacement (CMOD) was considered as an important parameter at the beginning but after Wells [4] coined the term Crack Tip Opening Displacement (CTOD) in 1963, it became the most important parameter for the determination of the criticality of the crack as it is the measure of the plastic strain at the crack tip. Stress Intensity Factor (SIF), is another very important parameter in Linear Elastic Fracture Mechanics (LEFM). The whole stress field at the crack tip can be derived if SIF is known. Crack extension takes place when the stresses and strains at the crack tip reaches a critical value, which is estimated by CTOD and the SIF. Other important crack parameters include plastic zone size and Crack Tip Opening Angle (CTOA).

These parameters depend on several factors which help in predicting about the crack. These parameters depend on the specimen geometry. The thickness of the specimen plays a vital role in determining the state of stress at the crack tip. A small change in the thickness leads to the variation of the other crack parameters. The thickness of the specimen also determines the plane stress and the plane strain criteria. If the thickness is small, the plane stress condition prevails at the crack tip, and in order to maintain plane strain at the crack tip, the thickness is kept sufficiently high. It works as a bridge for the transition from plane stress to plane strain. As the thickness increases, the near crack tip stress-strain field starts changing from plane stress to plane strain.

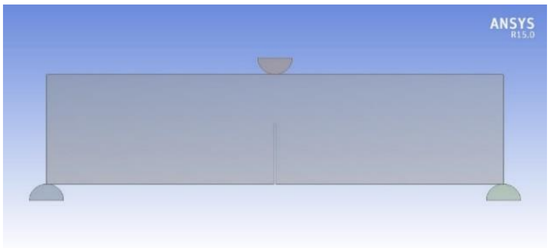
Several experimental and theoretical investigations have been carried out in the past to study the effect of the specimen geometry on the crack parameters. C. Michael Hudson and J. C. Newman Jr. [5] in 1973 studied the effect of the stress ratio and thickness of specimen on fatigue growth rate and fracture toughness for aluminum alloys using a servo hydraulic fatigue testing machine. Later in 1983, Murthy et.al [6] performed Photoelasticity test to investigate the effect of specimen thickness on the stress intensity factor for mode I fracture. Samer Mahmoud and Kevin Lease [7] performed fracture tests on aluminum specimen to investigate the effect of the thickness of the specimen on the Crack Tip Opening Angle (CTOA). Paleebut S. [8] measured CTOD and COD for compact tension specimens of different thickness.

Several numerical techniques have been used to solve the fracture mechanics problem and to obtain the crack parameters. Neuman Jr. et. al. [9] used finite element method to simulate and analyze the crack parameters for an aluminum alloy. V. Granados-Alejo et. al. [10] determined both experimentally and numerically the effect of specimen thickness on the fatigue behavior of notched steel plates. Abhijeeet Singh et.al.[11] used finite element tool ANSYS to compare the experimental and numerical results and used ANSYS to determine the effect of varying crack length and other crack dimension on the crack parameters, and hence proved ANSYS a suitable tool for such investigations.

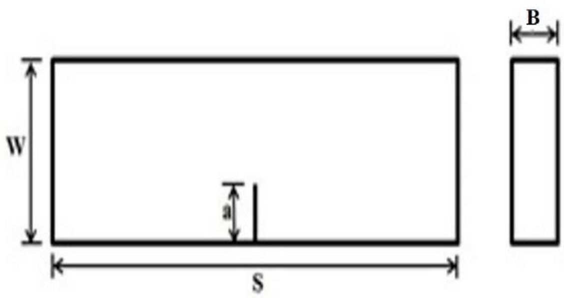
The present article uses the Finite Element Analysis (FEA) tool 'ANSYS' to numerically investigate the effect of varying specimen thickness on the different crack properties for a Side Edge Notched Bend (SENB) specimen under a three point loading system. The geometry of the specimen has been chosen according to the ASTM standards and the thickness varies from 8mm to 11mm for the specimen having a width of 20mm and length of 80mm with crack length varying such that 0.45≤a/W≤0.55.

2. NUMERICAL ANALYSIS

A simplified FEA simulation using ANSYS was performed for a three point bend specimen made of aluminum alloy (Al 6063-T6). The purpose of the numerical analysis is to check the effect of thickness on the different crack parameters. The analysis consists of two major steps: modeling of the specimen and applying the boundary condition for the analysis. A SENB specimen under three point bend was modeled as shown in figure1 using the properties of Al 6063-T6 as depicted in table 1.



(a)



(b)

Figure 1. Geometry of the specimen

The model prepared was meshed with a fine mesh as shown in figure 2. The mesh is finer at the crack tip and crack edge and a coarse mesh on the other parts. A higher number of nodes were chosen near the crack tip as it provides an accurate result.

Table 1. Mechanical properties of Al 6063-T6

Density	700 kg/mm^3
Tensile yield strength	214 MPa
Compressive yield strength	214 MPa
Modulus of elasticity	68.9 GPa
Poisson's ratio	0.33

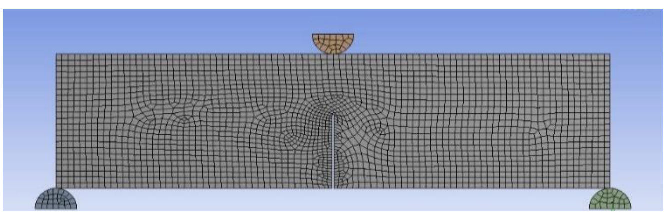


Figure 2. Meshed geometry

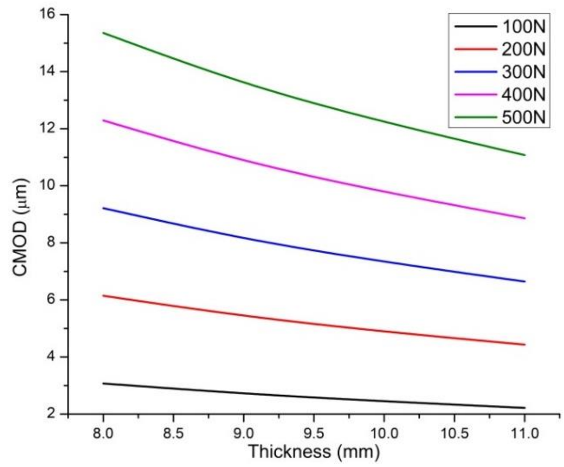
The thickness of the specimen varied from 8mm to 11mm with an interval of 1mm, and the crack length also varied from 9mm to 11mm following the ASTM standards. The boundary conditions were applied and the analysis was done for the entire range of geometry. The data obtained has been tabulated and documented in appendix 1.

3. RESULTS AND DISCUSSION

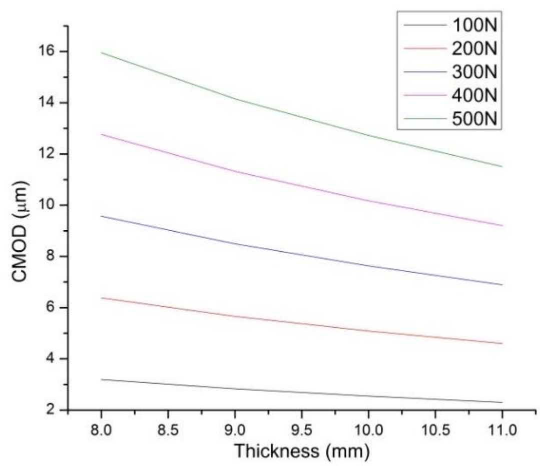
The results obtained have been documented and analyzed, and it has been noted that the variation of the thickness greatly affects the crack parameters. The varying crack length and the thickness both affect the crack property in a combined manner, and it has been studied that the thickness effect for different crack length is different.

3.1 Effect on the crack mouth opening displacement

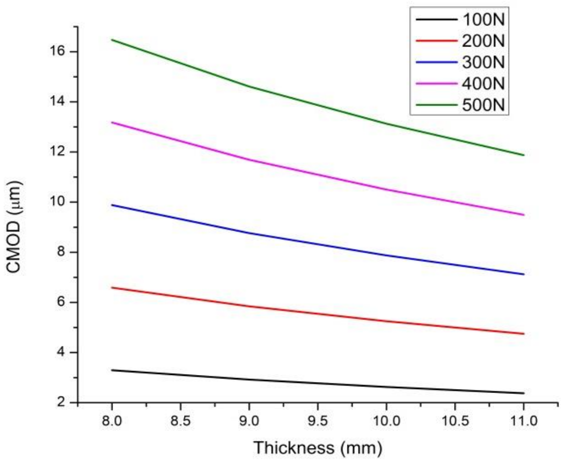
The effect of thickness on CMOD can be seen through figure 3 which shows the graph between thickness (X- axis) and CMOD (Y- axis). Figure 3 consists of three figures, showing the variation for each crack length. It can be clearly seen that with the increasing thickness, the CMOD value also drops. The CMOD shows a negative slope for an increase in thickness. With the increase in the crack length, the value of CMOD for a particular load and thickness increases.



(a) a = 9mm



(b) a = 10mm

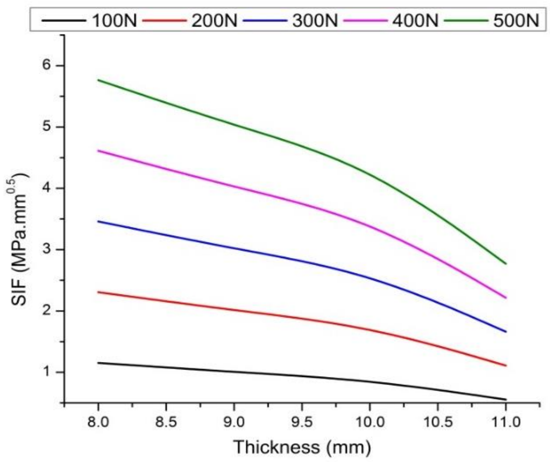


(c) a = 11mm

Figure 3. Variation of CMOD with thickness

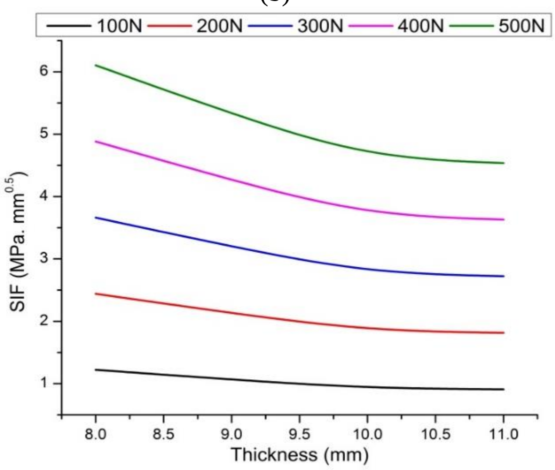
It can be clearly noted that the variation of the slope is very small when the thickness and the load is increased for all the crack lengths.

3.2 Effect on stress intensity factor

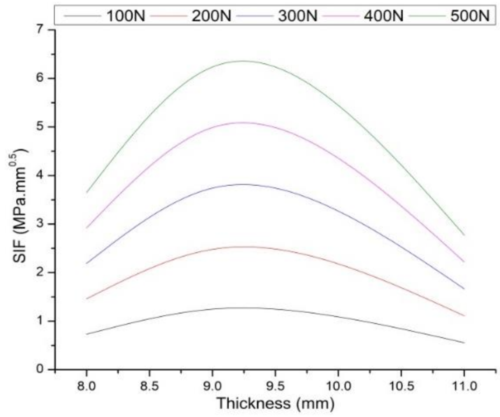


(a) a = 9mm

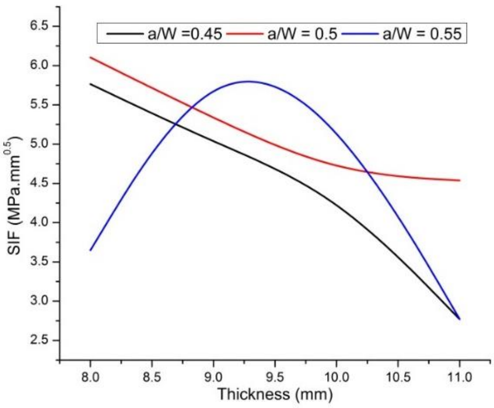
(b)



(c) a = 10mm



(c) a = 11mm



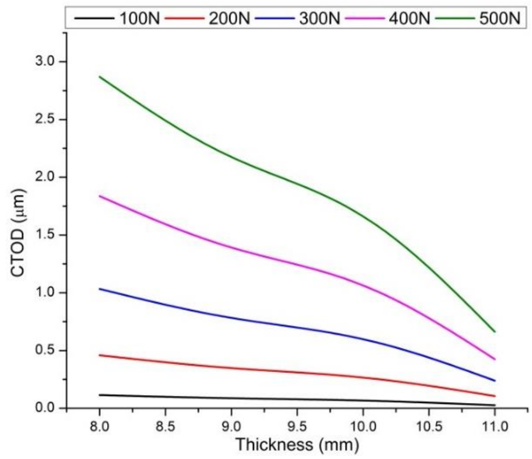
(d) SIF v/s B at 500N

Figure 4. Variation of SIF with thickness for different crack lengths

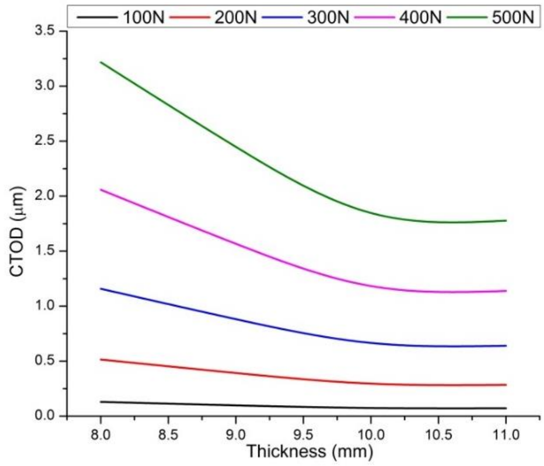
The variation of the stress intensity factor with the increase in thickness can be seen in figure 4, where the independent quantity 'thickness' is plotted on the abscissa and the dependent quantity 'SIF' is plotted on the ordinate. It can be derived from the graph that with the increase in thickness, the value of SIF decreases gradually and the state of stress at the crack tip changes from plane stress to plane strain, where the stress values are smaller as compared to the stresses during plane stress condition, and the change in the SIF values with the change in thickness is very small (figure 4(b)). An interesting point to be noted from figure 4 is the combined effect of crack length and the thickness. As the thickness and a/W ratio is increased, the stress condition at the crack tip shift towards plane stress, which means a higher value of stress at the crack tip (figure 4(d)).

3.3 Effect on crack tip opening displacement

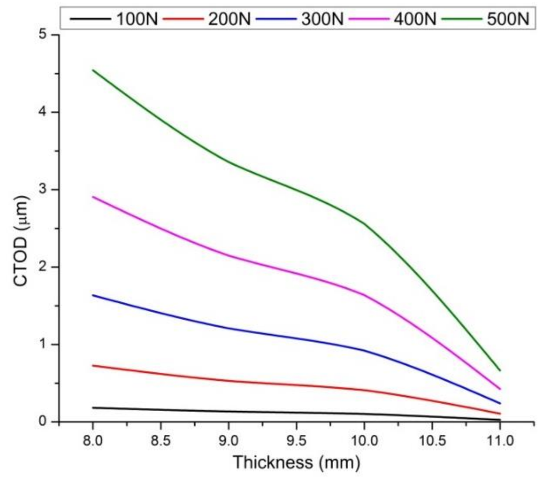
Figure 5 depicts the variation of CTOD with thickness of the specimen. It can be clearly seen that as the thickness is increased, the CTOD values drop. This drop in the value of CTOD is more dominant at higher loads as can be seen in figure 5, at 100N, the slope of the line is less as compared to the slope of the line at higher load. With the increase in thickness, the CTOD values starts converging, which shows the start of plane strain condition at the crack tip.



(a) a = 9mm



(b) a = 10mm



(c) a = 11mm

Figure 5. Variation of CTOD with specimen thickness

3.3 Effect on the plastic zone size

The effect of thickness on the plastic zone size as determined by the numerical analysis has been documented in table 2 and shown in figure 6. When the load or the crack length is increased, the plastic zone size increases, but with the increase in the thickness, the plastic zone size decreases. The state of stress at the crack tip influences the plastic zone size. On the other hand the, size of the plastic zone can be used to determine the state of stress. The plastic zone size gradually decreases from plane stress condition to plane strain condition. Figure 7 shows the shape of the plastic zone which remains the same despite the change in the thickness, but the size decreases as the thickness increases. Hence it can be concluded that with the change in thickness, the plastic zone size decreases and the state of stress at the crack tip gradually shifts to plane strain condition.

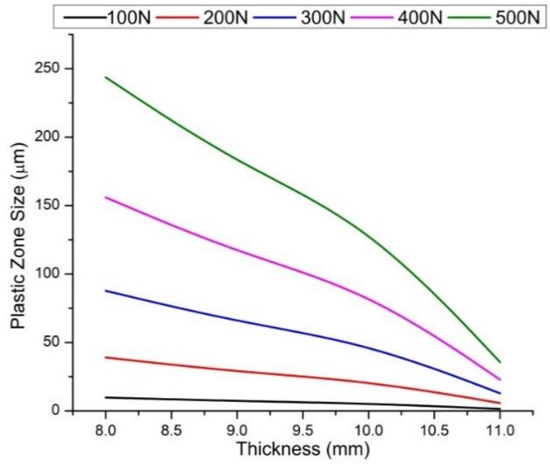
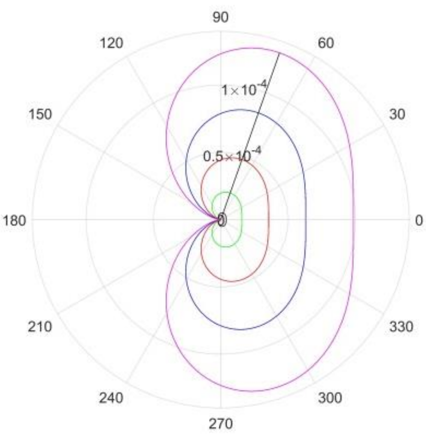
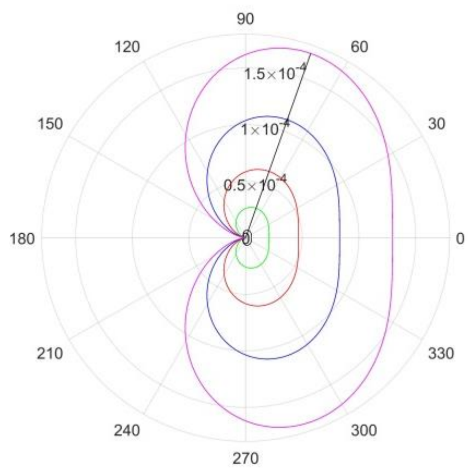


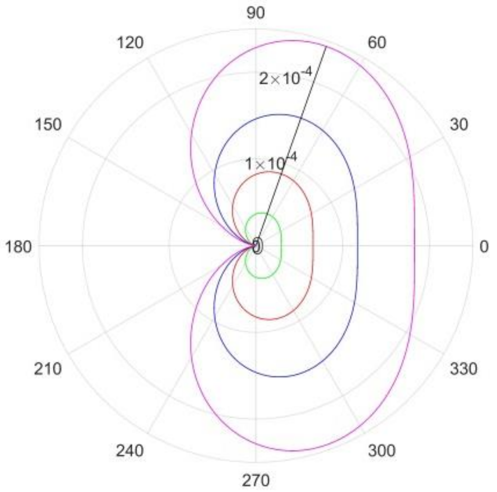
Figure 6. Variation of plastic zone size with thickness



(a)



(b)



(c)

Figure 7. Shape of plastic zone for different crack length and 100N load

4. CONCLUSION

The effect of specimen thickness on the various crack parameters has been successfully studied using the FEA tool ANSYS. The use of such tools is promoted as it saves time and energy, and can easily solve large number of problems very quickly and efficiently. Using the tool the crack parameters have been studied and analyzed. It was observed that:

- The CMOD decreases gradually and almost linearly. The slope was constant even after changing the load and the crack length.
- The SIF decreases with increase in the specimen thickness. The increase in thickness leads to the shifting of the state of stress from plane stress to plane strain. As the thickness increases, the change in the SIF seizes and the slope of the line gradually reaches zero, as is the case for plane strain condition.
- The CTOD decreases with the increase in the thickness. At light load, this decrease is small, but as the load is increased, the %age change in the value of CTOD increases with the change in thickness. Also as the load increases along with the thickness, the CTOD values starts converging at higher loads.
- The plastic zone size also decreases with the increase in thickness, and converges at higher load when both load and thickness varies. The plastic zone size can be used to determine the state of stress at the crack tip. The size of the plastic zone is smaller for plane strain condition as compared to the plane stress condition. Hence, the decrease in the plastic zone size reveals the shift from plane stress condition to plane strain condition.

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NOMENCLATURE

a	crack length (mm)
B	Thickness (mm)
K	Stress Intensity Factor (MPa.mm0.5)
S	Span Length (mm)
W	Width of the specimen (mm)

Appendix 1. Data acquired from the numerical analysis

Sl. No	Load (N)	Crack Length, a (mm)	Thickness, B(mm)	CMOD (µm)	CTOD (µm)	SIF, K ($MPa.mm^{0.5}$)	Plastic zone size (maximum) (µm)
1.	100	9	8	3.072	0.115	1.153	6.159
2.	200	9	8	6.144	0.459	2.306	24.636
3.	300	9	8	9.217	1.033	3.459	55.432
4.	400	9	8	12.29	1.837	4.612	98.545
5.	500	9	8	15.356	2.870	5.765	153.982
6.	100	9	9	2.725	0.087	1.004	4.670
7.	200	9	9	5.454	0.348	2.008	18.680
8.	300	9	9	8.173	0.783	3.012	42.030
9.	400	9	9	10.9	1.392	4.016	74.715
10.	500	9	9	13.625	2.176	5.019	116.744
11.	100	9	10	2.45	0.066	0.877	3.563
12.	200	9	10	4.9	0.266	1.754	14.254
13.	300	9	10	7.347	0.598	2.631	32.073
14.	400	9	10	9.796	1.063	3.508	57.017
15.	500	9	10	12.25	1.660	4.385	89.090
16.	100	9	11	2.215	0.027	0.554	1.422
17.	200	9	11	4.433	0.106	1.108	5.690
18.	300	9	11	6.644	0.239	1.662	12.801
19.	400	9	11	8.861	0.424	2.216	22.757
20.	500	9	11	11.076	0.663	2.77	35.557
21.	100	10	8	3.192	0.129	1.221	6.905
22.	200	10	8	6.381	0.515	2.441	27.617
23.	300	10	8	9.572	1.158	3.662	62.140
24.	400	10	8	12.766	2.059	4.883	110.467
25.	500	10	8	15.954	3.217	6.103	172.608
26.	100	10	9	2.831	0.098	1.065	5.256
27.	200	10	9	5.661	0.392	2.13	21.021
28.	300	10	9	8.493	0.881	3.195	47.298
29.	400	10	9	11.322	1.567	4.26	84.087
30.	500	10	9	14.156	2.448	5.325	131.383
31.	100	10	10	2.545	0.074	0.925	3.965
32.	200	10	10	5.09	0.296	1.85	15.861
33.	300	10	10	7.629	0.665	2.775	35.685
34.	400	10	10	10.174	1.182	3.7	63.443
35.	500	10	10	12.725	1.847	4.625	99.127
36.	100	10	11	2.299	0.071	0.907	3.815
37.	200	10	11	4.599	0.284	1.815	15.261
38.	300	10	11	6.892	0.640	2.722	34.333
39.	400	10	11	9.205	1.138	3.63	61.045
40.	500	10	11	11.507	1.778	4.537	95.383
41.	100	11	8	3.294	0.182	0.73	9.749
42.	200	11	8	6.587	0.727	1.46	38.994
43.	300	11	8	9.882	1.635	2.19	87.738
44.	400	11	8	13.176	2.907	2.919	155.976
45.	500	11	8	16.47	4.542	3.649	243.715
46.	100	11	9	2.922	0.134	1.247	7.204
47.	200	11	9	5.845	0.530	2.478	28.463
48.	300	11	9	8.766	1.208	3.741	64.839
49.	400	11	9	11.69	2.148	4.988	115.270
50.	500	11	9	14.612	3.357	6.235	180.109
51.	100	11	10	2.626	0.102	1.089	5.491
52.	200	11	10	5.25	0.409	2.177	21.965
53.	300	11	10	7.877	0.921	3.266	49.424
54.	400	11	10	10.502	1.637	4.355	87.863
55.	500	11	10	13.128	2.558	5.443	137.285
56.	100	11	11	2.375	0.027	0.555	1.425
57.	200	11	11	4.75	0.106	1.109	5.699
58.	300	11	11	7.122	0.239	1.664	12.823
59.	400	11	11	9.496	0.425	2.218	22.796
60.	500	11	11	11.873	0.664	2.773	35.618