MENG30011 Applied Solid Mechanics
AY 2022/23 coursework assessment

This assessment is designed to test your attainment of the Intended Learning Outcomes for MENG30011 Applied Solid Mechanics. The assessment is a single piece of coursework which carries 20 credits. The deadline for this coursework is **12:00 noon on Thursday 15th December 2022**.

This coursework has three parts. In Part A, you will analyse a mechanical component design using FEA and report on its suitability for service. In Part B you will answer questions about finite element theory. In Part C you will answer questions about the failure of materials. The three parts contribute separately to your overall unit mark; the weighting is Part A: 40%, Part B: 20%, Part C: 40%.

You should hand in your work via Turnitin on the unit Blackboard page. There are separate page limits for each part. These must include all figures, references and appendices. If you exceed the page limit for any part, your response for that part will not be accepted. You should put your responses together and submit them as a single .pdf document without a cover sheet.

This coursework must be done individually. You may discuss the coursework with other students but all work that you hand in, and any underlying analysis, **must be entirely your own**[1].

Harry Coules & Alexander Velichko, 07/10/2022

Part A: FEA Investigation and Report

Introduction

Liquified Natural Gas (LNG) carriers are tanker vessels that move LNG between major ports (see Figure 1). Natural gas is an important source of energy, and its large-scale transport allows the international energy market to operate efficiently while reducing the need for intercontinental pipelines. For transport by LNG carrier, natural gas is liquified by cooling in a special plant. The cold LNG is then pumped into large tanks onboard the carrier vessel. As the vessel sails between ports, gradual warming of the stored LNG inevitably causes some of it to boil off. To prevent a build-up of boil-off gas from over-pressurising the tanks, it must be re-liquified or gradually released. Any released boil-off gas is either: a.) diverted to the ship's engines, or b.) simply burned off so that only combustion products are released into the environment, rather than the more environmentally-damaging gas itself. LNG carriers use a large Gas Combustion Unit (GCU) to burn boil-off gas that cannot be either consumed by the engines or re-liquified and returned to the tanks. GCU modules are constructed in a factory and then lifted into place during fitting-out of the LNG carrier.

You are a stress analyst on the design team of a major supplier for GCUs to the marine LNG transport industry. Your team is a part of a company project which aims to design a new low-cost type of large GCU for bulk LNG carriers and bring it to market. The new design is almost complete, and your team are now finalising the design of its lifting attachments. Other team members have suggested a design for a lifting lug to support the GCU as it is lifted into place on the ship. The lugs are used during lifting operations only: different attachments secure the GCU to the ship. The Team Leader asks you to perform stress analysis on the part and produce a written report that the team can use to justify their proposal to the Project Lead.

[1] As in any summative assessment, all instances of suspected plagiarism will be reported to the Exam Board.

Figure 1: The Japanese-flagged Energy Innovator is an example of a modern LNG carrier. The GCU is installed in the blue exhaust stack towards the stern.

Design details

The lifting lug design is designed to keep the GCU stable as it is lifted, while avoiding a set of hydraulic control lines and instrumentation cables on the side of the unit. The lug designed by the team is shown in Figure 2. This shape will be fabricated from S355JR structural steel of a uniform thickness and welded to the rigid sidewall of the GCU using two welds. The integrity of the welds will be considered by a separate team and does not need to be included in your analysis. The dimensions *a, b* and *c* shown in Figure 2 and the thickness of material used to fabricate the lifting lug are given in Table 2 below.

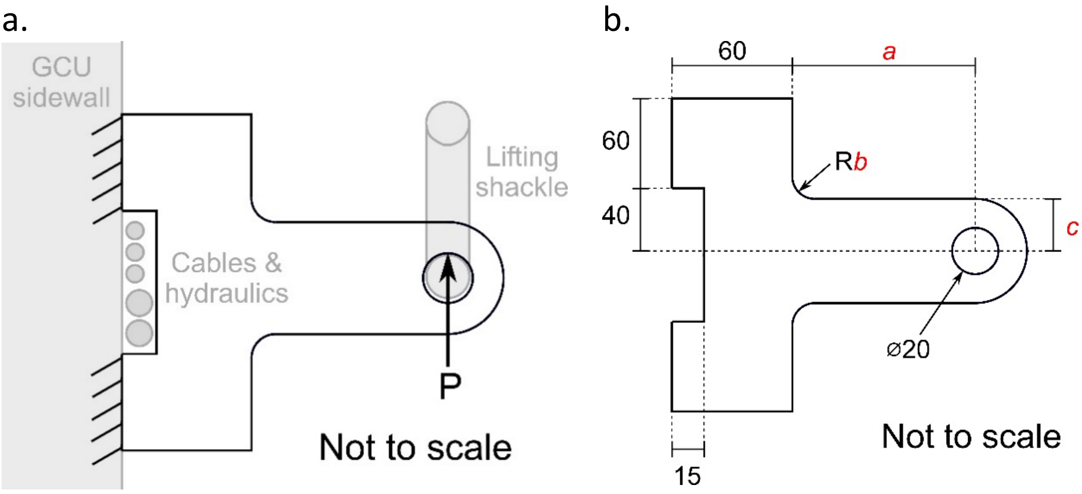

Figure 2: Proposed design of the GCU lifting lug. a.) Overall design showing loading and attachments to the GCU body. b.) Dimensions of the lifting lug (in mm). The values of dimensions a and b can be found in Table 2.

The lifting arrangement used to install the GCU is shown in Figure 3. The GCU is roughly cylindrical and six lifting lugs of the type shown in Figure 2 are positioned around its circumference so that the load is shared roughly equally between them. The overall mass of the GCU is 36,000 kg. It is essential that the GCU can be lifted safely during installation, and that the lifting lugs will not break. For lifting equipment of this type, a typical safety factor is:

$$\frac{Breaking\ strength\ of\ the\ component}{Safe\ working\ load} \approx 5$$

The breaking strength of a component is the maximum load that it will support (e.g. when tested to destruction). The safe working load is the load below which a component is intended to be used normally without fear of it breaking.

Table 1: Ambient-temperature mechanical properties of the structural steel which will be used for the lifting lugs (Steel, EN 10025-2 – S355JR).

Property	**Value**
Young's modulus	209 GPa
Poisson's ratio	0.3
Yield strength[2]	355 MPa
Ultimate tensile strength	630 MPa
Elongation at failure	22%
Density	8010 kg m^{-3}

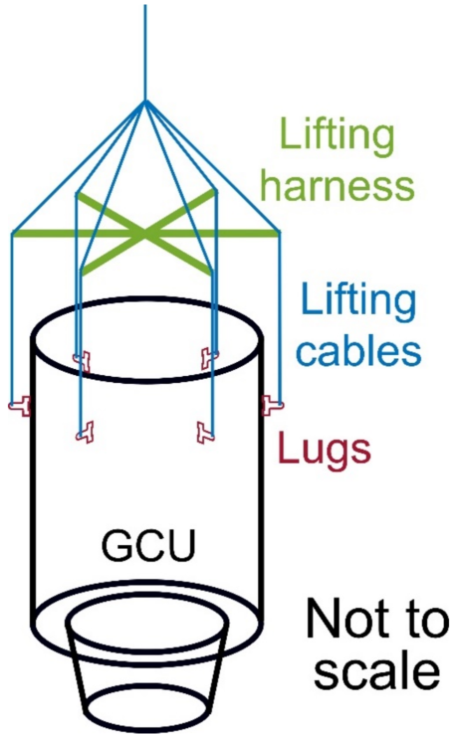

Figure 3: Vertical lifting arrangement to be used for installing the GCU. Six lugs are spaced equally around the circumference of the object. It can be assumed that all cables, shackles and harnesses used in the lifting operation will be appropriate for the loads involved.

Report

You must produce a report on your analysis. This report will be delivered to the Project Lead, who will make the final decision on whether to go ahead with this design. In your report, you should:

- Briefly outline the problem that you are aiming to solve.
- Explain and justify any analysis methods that you have used.
- Use appropriate methods to demonstrate that your stress analysis results are valid[3].
- Clearly present and interpret the results of your stress analysis.

[2] Specifically, this refers to the minimum allowable 0.2% offset yield strength.
[3] For example, these might include mesh sensitivity studies or comparisons to analytical solutions.

- Give a clear and well-justified recommendation on whether the lifting lug design is adequate or whether there is a potential safety hazard.

Additionally, the Team Leader has asked you to include two specific pieces of information in the report and **highlight them in yellow**:

- The maximum vertical deflection of the end of the lifting lug (i.e. the furthest point from the GCU wall) that would be expected during the lifting operation.
- The maximum value of von Mises' stress anywhere on the lug, **excluding the contact region between the lug and lifting shackle**, that would be expected during the lifting operation.

You may use any format or structure for the report – there is no set template. However, it must not exceed **4 sides** of A4 and you must use 11-point font or larger. Any figures, tables, equations, references and appendices must be included within this limit. You can assume that the Project Lead has a good knowledge of stress analysis, FEA and mechanics of materials.

You must decide what sort of FEA to perform and what software you use. You could use Abaqus[4], MATLAB[5], any of the FEA packages suggested in the formative coursework information, or any other software that you want. However, in the report you must carefully explain and justify any analysis that you have performed.

Part A report marking

Your Part A report will be marked on three criteria:

- Accuracy (30%) – The numerical accuracy of the results presented.
- Credibility (50%) – The overall persuasiveness of your report and its conclusions. This includes the quality of the analysis and how well-justified it is, the credibility of any arguments that you make, and how well these arguments are explained in relation to the boarder context of the work (e.g. any existing literature).
- Presentation (20%) - The quality of presentation seen in the written report, including figures etc. Sensible formatting and margin sizes should be used.

Each report will be marked individually. Marking will follow the University's standard 21-point scale. Marks for each of the criteria with be weighted and then summed together. This total mark will be converted to an overall percentage for Part A.

[4] This assessment is designed so that it can be done using the Learning Edition of Abaqus rather than the full version if necessary. However, for practical reasons this is discouraged. Although you will not be marked down for using Learning Edition, the fact that this version of Abaqus only supports a very limited number of nodes will put a severe and unnecessary limitation on your model design.
[5] The example MATLAB functions given on the unit Blackboard can be used and/or modified as you wish.

Part B: Theory of FEA

Introduction

Part B of this coursework comprises a single theory task. You should answer it using no more than **3 sides** of A4 with 11-point font or larger. You may use equations and/or figures if you want to; they are included in the page limit. You may use any layout you like for your response to Part B so long as it is clear; there is no fixed template.

Task

Download the Part B.zip file. Extract it and then run the enclosed .p code in MATLAB using[6]:

```
>> PartB(*my_student_code*)
```

replacing `* my_student_code*` with your own 7-digit student code. You do not need to run the contents of the folder named `Mesh2d v24`; these are functions that are called by `PartB.p`

When you run `PartB.p`, you will see two figures: Figure 1 shows a 2D domain which has been discretised using a mesh made up of Constant Strain Triangle elements. Figure 2 shows a particular element from that mesh. The domain in Figure 1 represents a piece of isotropic linear-elastic material. You will also see information on the material's Young's modulus, its Poisson's ratio and whether it should be considered in plane stress or plane strain.

Now answer the following questions in your Part B report:

1. How many: a.) elements, b.) nodes and c.) degrees-of-freedom does the mesh in Figure 1 have?

2. What is the stiffness matrix of the element shown in Figure 2? You do not need to show a derivation of formulae for the stiffness matrix, but you should show your working.

3. Consider the element in Figure 2 alone. Imagine the situation where:

   - Nodes 2 & 3 are restrained against movement in both the x and y directions. Node 1 remains unrestrained.
   - Forces f_{1x} and f_{1y} are applied at Node 1 in the x and y directions. The values of these forces per unit thickness of material are given by the MATLAB script.

   What is the magnitude of the reaction force at Node 2? Show your working.

4. Consider the domain shown in Figure 1 again. If you knew:

   - The distribution of mass in the domain.
   - Its boundary conditions.
   - That any material damping was negligible.

   describe how you could find its natural frequencies of vibration. You do not need to determine these frequencies.

Part B marking

Your response to Part B will be marked based on:

[6] If this doesn't work, you may need to add the unzipped folder to your MATLAB path by right clicking on it in MATLAB and selecting Add to path>Selected folders and subfolders.

- The accuracy of your answers (primary criterion).
- Your use and explanation of methods (secondary criterion). Is an appropriate method being used/proposed? Is any working clear and straightforwardly explained?
- Presentation (secondary criterion). Your response must be clear and legible.

Your responses will be marked individually. Marking will follow the University's standard 21-point scale. The mark will be converted to a percentage for Part B.

Part C: Failure of Materials

Introduction

You are asked to complete two research investigations, related to the structural integrity of service systems on board the LNG carrier. To complete these tasks, you may need to perform some numerical calculations. You can use any software (for example, you can write a program in MATLAB). You do not need to show your code. However, you need to clearly describe all formulas and methods you are using. During your analysis you can use any reasonable approximations. It is important to clearly describe and justify them. You may use any layout you like for your response to Part C so long as it is clear; there is no fixed template.

Part C questions

Question 1

One of the load-bearing structural components represents a large plate with rectangular cross-section. The material is aluminium and has a yield stress of 400 MPa, an elastic modulus of 70 GPa, a Poisson's ratio of 0.3 and a fracture toughness of 20 MPa $\sqrt{\mathrm{m}}$. The plate is loaded by (unknown) normal stresses σ_x and σ_y as shown in Figure 4. In order to measure these stresses a test is performed. The stresses are calculated from strains, which are measured by strain gauges bonded to the plate. It is assumed that these stresses are not sufficient to cause yielding.

Q1a. *What is the smallest number of strain measurements required to determine σ_x and σ_y?*

Q1b. *Calculate applied stresses σ_x and σ_y from strain measurements.*

1) *Define the orientations of the necessary strain gauges.*
2) *The relevant strain values can be obtained using the MATLAB function provided.*

In order to ensure the structural integrity of the component during the service an additional stress σ_p must be taken into account. It is assumed the magnitude of this stress $|\sigma_p| \leq 400\ \mathrm{MPa}$ and its direction is defined by the angle $\theta_p = 30^0$ as shown in Fig.4. It is also assumed that a central crack of an arbitrary orientation can be developed due to environmental and loading conditions (see Fig. 4). The crack can be identified by ultrasonic non-destructive testing, however, the minimum detection size is 5 mm.

Q1c. *Provide analysis of the possible component's failure mechanisms as a function of stress σ_p and crack orientation.*

You can consider the following points:

1) Analyse safety factors, corresponding to different failure mechanisms.
2) Define the range of stress σ_p, which is safe for the structural integrity of the component.
3) Find the most dangerous orientation of the crack.
4) The results can be presented using diagrams, graphs, or tables.
5) Try to give a physical explanation of obtained results where it is possible.

In order to calculate strain gauge measurements for Q1b run the enclosed fn_strain.p code in MATLAB using

```
>> strain = fn_strain(my_student_code,theta)
```

and replacing `my_student_code` with your own 7-digit student code. The variable *theta* is a strain gauge orientation angle θ in degrees (see Fig.4) and can be a scalar or vector.

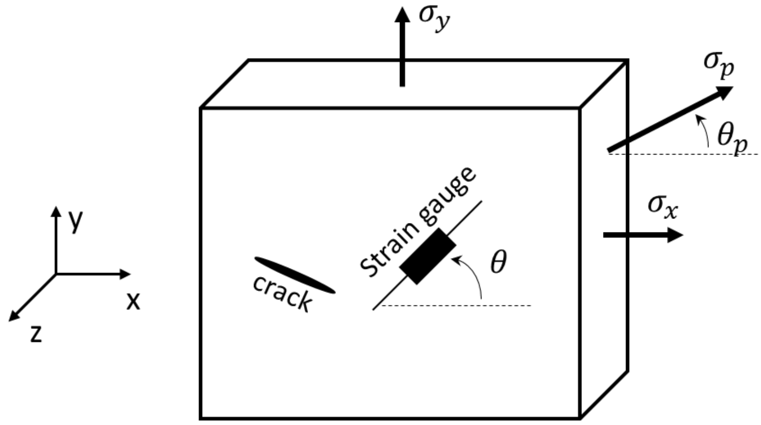

Figure 4: Stressed plate containing an inclined crack with a strain gauge attached.

Question 2

The LNG carrier has a complicated pipework which is required to support its service systems. It is very important to maintain structural integrity of the pipework, therefore, routine inspections must be performed in certain time intervals. One section of the pipework represents a steel pipe with closed ends, an outer diameter of D = 200 mm and a wall thickness of t = 10 mm. The pipe works in cycling loading with internal pressure varying from zero to p = 40 MPa and back. Additionally, there is a possibility of a valve fault which can cause a sudden short-term increase of the maximum working pressure by a factor of 2. It is assumed that during the service a semi-circular crack can occur in a pipe weld as shown in Figure 5. The pipe is regularly inspected, and the crack can be detected with probability of detection described by the function $P_{pod}(a)$, where a is the crack radius (the function $P_{pod}(a)$ corresponds to the probability that all cracks with the radius greater than a are detected).

The steel has a fracture toughness of K_{IC} = 90 MPa $\sqrt{\text{m}}$. The fatigue crack growth is described by Paris' law with constants $C = 10^{-12} \frac{\text{m/cycle}}{(\text{MPa}\sqrt{\text{m}})^m}$ and m = 4. The geometry correction factor for the semi-circular crack of radius a is given by:

$$Y = 0.728 + 0.373\left(\frac{a}{t}\right)^2 - 0.029\left(\frac{a}{t}\right)^4, a \leq t.$$

Q2a. *How does the pipe's probability of failure depend on the interval between pipe inspections?*

Q2b*. Find the inspection interval, corresponding to the probability of failure equal to 0.01.*

In order to calculate the probability of detection function $P_{pod}(a)$ run the enclosed fn_pod.p code in MATLAB using

```
>> p = fn_pod(my_student_code,a)
```

replacing `my_student_code` with your own 7-digit student code. The variable *a* is a crack radius in millimetres and can be a scalar or vector.

Tips:

1) *Determine the failure mechanism first.*
2) *The inspection interval can be measured in terms of the number of cycles.*

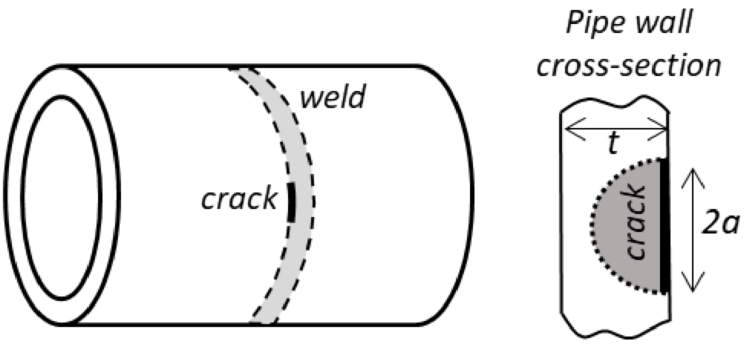

Figure 5: Service pipework containing a crack in the radial-circumferential plane.

Part C marking

Your responses to Part C will be marked based on:

- The correctness of your answers.
- The understanding of the methods involved.
- Presentation. Your explanations must be clear and legible.

Your responses will be marked individually. Marking will follow the University's standard 21-point scale. The mark will be converted to a percentage for Part C.

Appendix: Lifting lug dimensions for Part A

In Part A, each candidate will analyse a lug of unique design. The lug dimensions that should be used by each candidate are given in Table 2, ordered by student code. Use your 7-digit student code to determine the values of a, b, c and t (thickness) that you should use.

Table 2: Dimensions of the lifting lug to be considered by each candidate.

Student code	a (mm)	b (mm)	c (mm)	thickness (mm)
1531251	70	40	30	30
1800708	70	40	30	32.5
1805922	70	40	30	35
1820499	70	40	32.5	30
1839288	70	40	32.5	32.5
1839815	70	40	32.5	35
1847047	70	40	35	30
1857219	70	40	35	32.5
1859176	70	40	35	35
1900444	70	45	30	30
1901327	70	45	30	32.5
1903913	70	45	30	35
1904306	70	45	32.5	30
1904894	70	45	32.5	32.5
1904930	70	45	32.5	35
1907015	70	45	35	30
1907378	70	45	35	32.5
1909131	70	45	35	35
1913974	70	50	30	30
1914413	70	50	30	32.5
1915056	70	50	30	35
1915370	70	50	32.5	30
1915577	70	50	32.5	32.5
1915585	70	50	32.5	35
1915835	70	50	35	30
1922384	70	50	35	32.5
1929936	70	50	35	35
1932179	70	55	30	30
1932286	70	55	30	32.5
1934756	70	55	30	35
1935805	70	55	32.5	30
1936285	70	55	32.5	32.5
1936453	70	55	32.5	35
1936945	70	55	35	30
1937669	70	55	35	32.5
1937850	70	55	35	35
1938848	75	40	30	30
1940730	75	40	30	32.5
1943414	75	40	30	35

Student code	a (mm)	b (mm)	c (mm)	thickness (mm)
1944637	75	40	32.5	30
1946274	75	40	32.5	32.5
1958722	75	40	32.5	35
1972250	75	40	35	30
1973031	75	40	35	32.5
1973074	75	40	35	35
1974620	75	45	30	30
2000284	75	45	30	32.5
2000683	75	45	30	35
2000863	75	45	32.5	30
2002632	75	45	32.5	32.5
2002667	75	45	32.5	35
2002695	75	45	35	30
2002820	75	45	35	32.5
2003420	75	45	35	35
2003879	75	50	30	30
2003933	75	50	30	32.5
2005902	75	50	30	35
2006664	75	50	32.5	30
2006679	75	50	32.5	32.5
2006847	75	50	32.5	35
2007122	75	50	35	30
2007824	75	50	35	32.5
2008767	75	50	35	35
2008918	75	55	30	30
2008959	75	55	30	32.5
2009028	75	55	30	35
2010407	75	55	32.5	30
2010521	75	55	32.5	32.5
2010683	75	55	32.5	35
2011110	75	55	35	30
2011644	75	55	35	32.5
2011745	75	55	35	35
2011809	80	40	30	30
2011862	80	40	30	32.5
2012109	80	40	30	35
2012800	80	40	32.5	30
2012804	80	40	32.5	32.5
2012815	80	40	32.5	35
2013500	80	40	35	30
2013640	80	40	35	32.5
2014459	80	40	35	35
2014606	80	45	30	30
2015242	80	45	30	32.5
2015329	80	45	30	35

Student code	a (mm)	b (mm)	c (mm)	thickness (mm)
2015454	80	45	32.5	30
2016852	80	45	32.5	32.5
2016955	80	45	32.5	35
2017124	80	45	35	30
2017408	80	45	35	32.5
2017620	80	45	35	35
2017949	80	50	30	30
2017962	80	50	30	32.5
2018122	80	50	30	35
2018717	80	50	32.5	30
2022281	80	50	32.5	32.5
2022947	80	50	32.5	35
2023463	80	50	35	30
2030919	80	50	35	32.5
2031587	80	50	35	35
2032425	80	55	30	30
2034182	80	55	30	32.5
2034223	80	55	30	35
2034933	80	55	32.5	30
2039183	80	55	32.5	32.5
2039711	80	55	32.5	35
2040966	80	55	35	30
2042634	80	55	35	32.5
2042710	80	55	35	35
2043303	85	40	30	30
2043623	85	40	30	32.5
2044316	85	40	30	35
2044449	85	40	32.5	30
2044546	85	40	32.5	32.5
2046106	85	40	32.5	35
2046826	85	40	35	30
2047448	85	40	35	32.5
2047474	85	40	35	35
2048600	85	45	30	30
2049040	85	45	30	32.5
2049155	85	45	30	35
2050825	85	45	32.5	30
2050899	85	45	32.5	32.5
2051568	85	45	32.5	35
2051713	85	45	35	30
2051796	85	45	35	32.5
2051988	85	45	35	35
2052844	85	50	30	30
2054100	85	50	30	32.5
2054379	85	50	30	35

Student code	a (mm)	b (mm)	c (mm)	thickness (mm)
2055371	85	50	32.5	30
2055707	85	50	32.5	32.5
2055745	85	50	32.5	35
2055792	85	50	35	30
2055853	85	50	35	32.5
2059727	85	50	35	35
2059728	85	55	30	30
2059811	85	55	30	32.5
2060463	85	55	30	35
2061182	85	55	32.5	30
2062153	85	55	32.5	32.5
2063472	85	55	32.5	35
2064398	85	55	35	30
2064558	85	55	35	32.5
2064844	85	55	35	35
2065424	90	40	30	30
2065759	90	40	30	32.5
2066239	90	40	30	35
2066245	90	40	32.5	30
2067728	90	40	32.5	32.5
2068178	90	40	32.5	35
2068409	90	40	35	30
2068656	90	40	35	32.5
2071528	90	40	35	35
2074204	90	45	30	30
2074754	90	45	30	32.5
2075340	90	45	30	35
2081747	90	45	32.5	30
2087849	90	45	32.5	32.5
2090671	90	45	32.5	35
2337888	90	45	35	30
2341547	90	45	35	32.5
2342316	90	45	35	35
2343120	90	50	30	30
2343636	90	50	30	32.5
2345139	90	50	30	35
2053620	90	50	32.5	30