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UNIVERSITI SAINS MALAYSIA

First Semester Examination  
2014/2015 Academic Session

December 2014 / January 2015

**EMM331 – Solid Mechanics**  
**[Mekanik Pepejal]**

Duration : 3 hours  
[Masa : 3 jam]

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Please check that this paper contains **EIGHT** printed pages, **SIX** pages appendix and **FIVE** questions before you begin the examination.

*[Sila pastikan bahawa kertas soalan ini mengandungi **LAPAN** mukasurat, **ENAM** mukasurat lampiran dan **LIMA** soalan yang bercetak sebelum anda memulakan peperiksaan.]*

**Appendix/Lampiran:**

- |                                 |                    |
|---------------------------------|--------------------|
| 1. Formulas for Solid Mechanics | [1 page/mukasurat] |
| 2. For use in Q3[a]             | [1 page/mukasurat] |
| 3. For use in Q3[b]             | [2 page/mukasurat] |
| 4. For use in Q4[a]             | [1 page/mukasurat] |
| 5. For use in Q5[b]             | [1 page/mukasurat] |

**INSTRUCTIONS** : Answer **ALL** questions.

*[**ARAHAN** : Jawab **SEMUA** soalan.]*

Answer questions in English OR Bahasa Malaysia.

*[Jawab soalan dalam Bahasa Inggeris ATAU Bahasa Malaysia.]*

Answer to each question must begin from a new page.

*[Jawapan bagi setiap soalan mestilah dimulakan pada mukasurat yang baru.]*

*In the event of any discrepancies, the English version shall be used.*

*[Sekiranya terdapat sebarang percanggahan pada soalan peperiksaan, versi Bahasa Inggeris hendaklah diguna pakai.]*

**Q1. [a] With the help of sketches, provide brief answers to the following questions:**

- [i] Define strain energy density and show it in stress-strain graph.**
- [ii] Distinguish between modulus of elasticity and modulus of resilience.**

*Dengan bantuan lakaran, berikan jawapan ringkas bagi soalan di bawah:*

- [i] Takrifkan ketumpatan tenaga terikan dan tunjukkannya pada graf tegasan-terikan.*
- [ii] Bezakan antara modulus kekenyalan dan modulus keliatan.*

**(30 marks/markah)**

**[b] A steel cantilever beam shown in Figure Q1[b] is a uniform solid circular cross-section and carries a vertical load  $F$  at its free end C. Given that the vertical deflection of C and the bending stress in the cantilever are 2.5 mm and 100 MPa respectively, determine:**

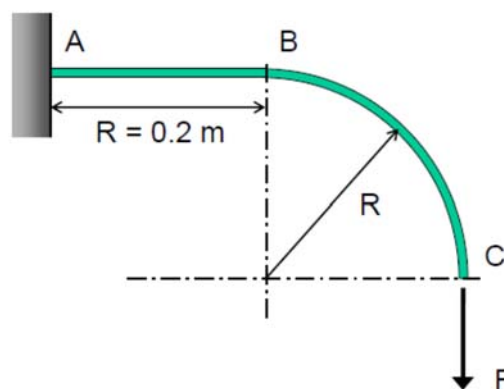
- [i] the value of load  $F$ , and**
- [ii] a suitable diameter,  $d$ , for the cross section using Castigliano's theorem.**

**Use Young's modulus  $E = 210$  GPa for steel.**

*Sebuah rasuk jalur keluli seperti ditunjukkan pada Rajah S1[b] mempunyai keratan rentas bulatan pejal yang sekata dan dikenakan daya menegak  $F$  pada penghujung C. Diberikan pesongan menegak pada C dan tegasan lentur bagi rasuk julur masing-masing ialah 2.5 mm dan 100 MPa, tentukan:*

- [i] nilai daya  $F$ , dan*
- [ii] diameter yang sesuai,  $d$ , bagi keratan rentas rasuk dengan menggunakan teorem Castigliano.*

*Gunakan modulus Young  $E = 210$  GPa bagi keluli.*



**Figure Q1[b]**  
*Rajah S1[b]*

**(70 marks/markah)**

Q2. [a] A steel has Young's modulus  $E$  and yield point  $\sigma_y$ . With the aid of stress-strain graphs as the responses for strain inputs:

- [i] Describe elastic-perfectly plastic and elastic-linear hardening deformation model under monotonic loading and sketch related rheological model, and
- [ii] Explain the effect of plastic deformation model to the behavior of the steel when the strain input is removed. Apply elastic-perfectly plastic and elastic-linear hardening models in separate modelling. Both models have the same value of strain input.

*Keluli mempunyai modulus Young  $E$  dan titik alahan  $\sigma_y$ . Dengan bantuan graf tegasan-terikan sebagai respon kepada input terikan:*

- [i] jelaskan maksud model ubah bentuk elastik plastik sempurna dan elastik pengerasan linear di bawah bebanan monotonik dan lakarkan model reologi yang berkaitan, dan*
- [ii] terangkan kesan model ubah bentuk plastik terhadap perilaku keluli apabila input terikan disingkirkan. Gunakan model elastik plastik sempurna dan elastik plastik pengerasan linear bagi setiap pemodelan secara berasingan. Kedua-dua model dikenakan input terikan yang sama.*

(40 marks/markah)

[b] Consider the stress-strain data in Table Q2[b] for a steel tempered at 300°C. Obtain values of the constants for a stress-strain curve of the Ramberg-Osgood form that fits these data. Calculate stress-strain values based on the obtained Ramberg-Osgood model and compare your prediction with data in Table Q2[b] (choose at least 3 points).

*Pertimbangkan data tegasan-terikan pada Jadual S2[b] bagi keluli yang diwaja pada suhu 300°C. Dapatkan nilai-nilai pekali bagi lengkung tegasan-terikan dalam bentuk persamaan Ramberg-Osgood yang sepadan dengan data berkenaan. Kirakan nilai tegasan-terikan berdasarkan model Ramberg-Osgood yang diperolehi dan bandingkan pengiraan tersebut dengan data pada Jadual S2[b] (pilih sekurang-kurangnya 3 titik).*

**Table Q2[b]**  
*Jadual S2[b]*

$\sigma$ , MPa	$\epsilon$ , %	$\sigma$ , MPa	$\epsilon$ , %
0	0.000	1522	0.951
276	0.135	1683	1.308
553	0.276	1803	1.751
829	0.421	1889	2.240
1102	0.573	1970	3.000
1303	0.706	2013	3.760
1406	0.799		

(60 marks/markah)

- Q3. [a] A stepped shaft, as shown in Figure Q3[a], has a 50 mm diameter for a length of 100 mm and then it is stepped down to 25 mm diameter for a further 100 mm to the free end. At this point a load of 2.68 kN is applied. If the limiting design bending stress is 280 MPa, determine a suitable value for the fillet radius at the change of section.

*Sebuah aci berlangkah seperti Rajah S3[a] mempunyai diameter 50 mm sepanjang 100 mm dan kemudian saiznya direndahkan kepada diameter 25 mm sepanjang 100 mm sehingga penghujung aci. Dayasebanyak 2.68 kN dikenakan pada penghujung aci. Sekiranya tegasan lenturan bagi had rekabentuk ialah 280 MPa, tentukan nilai yang sesuai bagi jejari fillet pada pertukaran bahagian aci.*

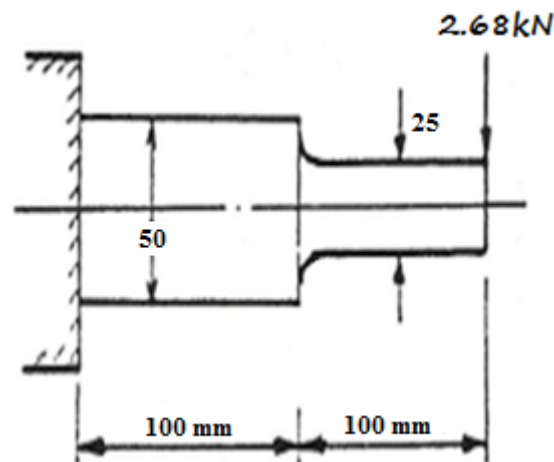


Figure Q3[a]  
Rajah S3[a]

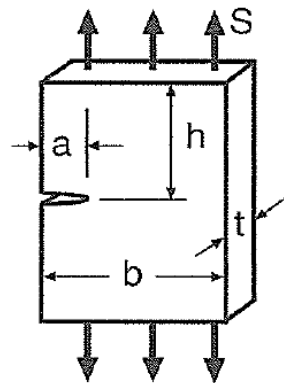
(40 marks/markah)

[b] An engineering component is to be made of Ni maraging steel. The component is a plate loaded in tension, and it may have a crack in one edge as shown in Figure Q3[b]. The plate dimensions are  $b = 35\text{mm}$  and  $t = 5\text{mm}$ , and the crack may be as long as  $a = 10\text{ mm}$ . The component must resist a tension force of  $P = 50\text{kN}$ .  $K_{Ic}$  for Ni Maraging steel is  $176\text{ MPa}\sqrt{\text{m}}$ . Refer to Appendix 3 for other useful details for calculations to determine:

- [i] The safety factor against brittle failure
- [ii] The safety factor against fully plastic yielding
- [iii] The overall (controlling) safety factor

*Satu komponen kejuruteraan telah dihasilkan daripada keluli Ni maraging. Komponen itu adalah satu plat yang dibeban secara tegangan, dan boleh mengandungi retak pada satah seperti tertera di Rajah S3[b]. Dimensi plat diberikan sebagai  $b = 35\text{ mm}$  dan  $t = 5\text{mm}$  dan retak boleh sepanjang  $a = 10\text{ mm}$ . Komponen itu perlu menahan daya tegangan sebanyak  $P = 50\text{kN}$ .  $K_{Ic}$  bagi keluli Ni Maraging adalah  $176\text{ MPa}\sqrt{\text{m}}$ . Rujuk Lampiran 3 untuk perincian lain pengiraan bagi menentukan:*

- (i) *Faktor keselamatan dalam mengekang kegagalan rapuh*
- (ii) *Faktor keselamatan dalam mengekang alah plastik sepenuhnya*
- (iii) *Faktor keselamatan keseluruhan (kawalan)*



**Figure Q3[b]**  
*Rajah S3[b]*

(60 marks/markah)

- Q4. [a] A bending member has a rectangular cross section of dimensions as shown in Figure Q4[a] of depth  $b = 60\text{mm}$  and thickness  $t = 12\text{mm}$ . It is made of AISI 4340 steel (see Table Q4) and is subjected to a cyclic moment between  $M_{\min} = 0.8$  and  $M_{\max} = 4.0\text{kNm}$ . Failure occurred after 60,000 cycles of this loading by brittle fracture from a through-thickness edge crack extending 14mm in the depth direction. Estimate the initial crack length present at the beginning of the cyclic loading. Refer to Appendix 4 for calculation details.

Satu anggota yang melentur mempunyai keratan rentas segiempat seperti tertera pada Rajah S4[a] mempunyai dimensi kedalaman  $b = 60\text{mm}$  dan ketebalan  $t = 12\text{mm}$ . Bahan anggota adalah keluli AISI 4340 (rujuk Jadual S4) dikenakan beban momen berkitar di antara  $M_{\min} = 0.8$  dan  $M_{\max} = 4.0\text{kNm}$ . Kegagalan rapuh berlaku pada 60,000 kitar setelah retak memanjang sebanyak 14mm pada arah ke dalaman retak. Anggarkan panjang retak awal pada permulaan beban kitar. Rujuk Lampiran 4 untuk perincian penyelesaian.

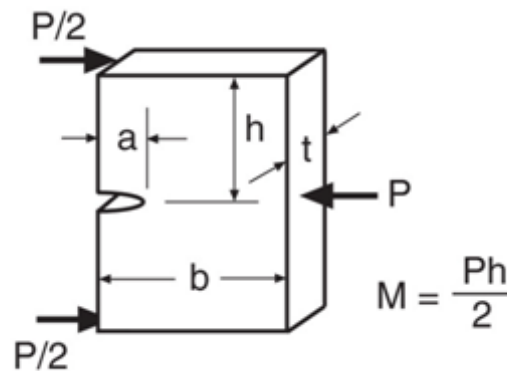


Figure Q4[a]  
Rajah S4[a]

Table Q4  
Jadual S4

Material	Yield $\sigma_o$ MPa (ksi)	Toughness $K_{Ic}$ MPa $\sqrt{m}$ (ksi $\sqrt{in}$ )	Walker Equation				
			$C_0$ mm/cycle (MPa $\sqrt{m}$ ) <sup>m</sup>	$C_0$ in/cycle (ksi $\sqrt{in}$ ) <sup>m</sup>	$m$	$\gamma$ ( $R \geq 0$ )	$\gamma$ ( $R < 0$ )
AISI 4340 steel ( $\sigma_u = 1296\text{ MPa}$ )	1255 (182)	130 (118)	$5.11 \times 10^{-10}$	$2.73 \times 10^{-11}$	3.24	0.420	0

(70 marks/markah)

- [b] Answer TRUE or FALSE to the statement made in underlined italics. Explain clearly the reasons for your conclusion.

*Jawab Benar atau Salah kepada kenyataan condong dan bergaris di bawah. Terangkan dengan jelas alasan yang diberikan.*

**Long catastrophic fractures often occur in steel structures if the load is maintained during crack propagation. A failure which exhibits ductile behavior at the origin will continue to do so along the remainder of the crack path.**

*Retak panjang malapetaka selalunya terjadi pada struktur keluli sekiranya beban ditetapkan semasa retak merambat. Kegagalan yang menunjukkan sifat mulur pada permulaan akan tetap bersifat sama di sepanjang laluan retak.*

(30 marks/markah)

- Q5. [a] Consider metals, polymers and concrete. Which of these classes of materials typically exhibit strong recovery of creep strain after unloading, and which do not? Briefly explain in terms of the physical mechanism of creep why the strains are generally recovered or why they are not recovered for each class of materials.

*Pertimbangkan bahan iaitu logam, polimer dan konkrit. Yang manakah antara bahan ini menunjukkan pemulihan terikan rayapan yang kuat selepas beban di keluarkan dan yang manakah sebaliknya. Terangkan dengan ringkas melalui mekanisme fizikal rayapan tentang pemulihan terikan atau tiada pemulihan terikan bagi setiap kelas bahan yang dibincangkan.*

(50 marks/markah)

- [b] An alloy steel tube of 100mm, diameter and a 3 mm wall thickness is to operate at 400 °C with internal pressure for a service life of 100000 hours.

Determine the allowable pressure for a creep strain limit of 0.5%.

The constants in the minimum creep equation at 400 °C are  $n = 3$  and  $B = 1.45 \times 10^{-23}$  per hour per  $\text{MN/m}^2$ .

Start your solution by relating the principal creep rates to Mises yield criterion.

Refer to Appendix 5 for calculation details.

*Satu tiub keluli berdiameter 100mm dan berketebalan 3mm dikehendaki beroperasi pada suhu 400 °C pada tekanan dalaman untuk hayat perkhidmatan selama 100000 jam.*

*Tentukan tekanan dalaman bagi had terikan rayapan sebanyak 0.5%.*

*Pemalar-pemalar minima bagi perhubungan rayapan pada suhu 400 °C adalah  $n = 3$  dan  $B = 1.45 \times 10^{-23}$  per jam per  $\text{MN/m}^2$ .*

*Penyelesaian dimulakan dengan mengaitkan kadar rayapan principal dengan kriteria alah Mises.*

*Rujuk Lampiran 5 untuk perincian pengiraan.*

**(50 marks/markah)**

## Formulas for Solid Mechanics

### Selected theories of failure

Tresca:

von Mises:

$$\sigma_1 - \sigma_3 = \sigma_Y$$

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2\sigma_Y^2$$

### Basic strain energy formulas

Load category	General Expression for strain energy	Particular case for constant load and geometry	Strain Energy per unit volume
Tension	$\int \frac{F^2}{2AE} dx$	$\frac{F^2 L}{2AE}$	$\frac{\sigma^2}{2E}$
Simple shear	$\int \frac{Q^2}{2AG} dx$	$\frac{Q^2 L}{2AG}$	$\frac{\tau^2}{2G}$
Torsion	$\int \frac{T^2}{2GJ} dx$	$\frac{T^2 L}{2GJ}$	$\frac{\tau_m^2}{4G}$ for circular section
Bending	$\int \frac{M^2}{2EI} dx$	$\frac{M^2 L}{2EI}$	$\frac{\sigma_m^2}{6E}$ for rectangular section

### Selected trigonometric applications

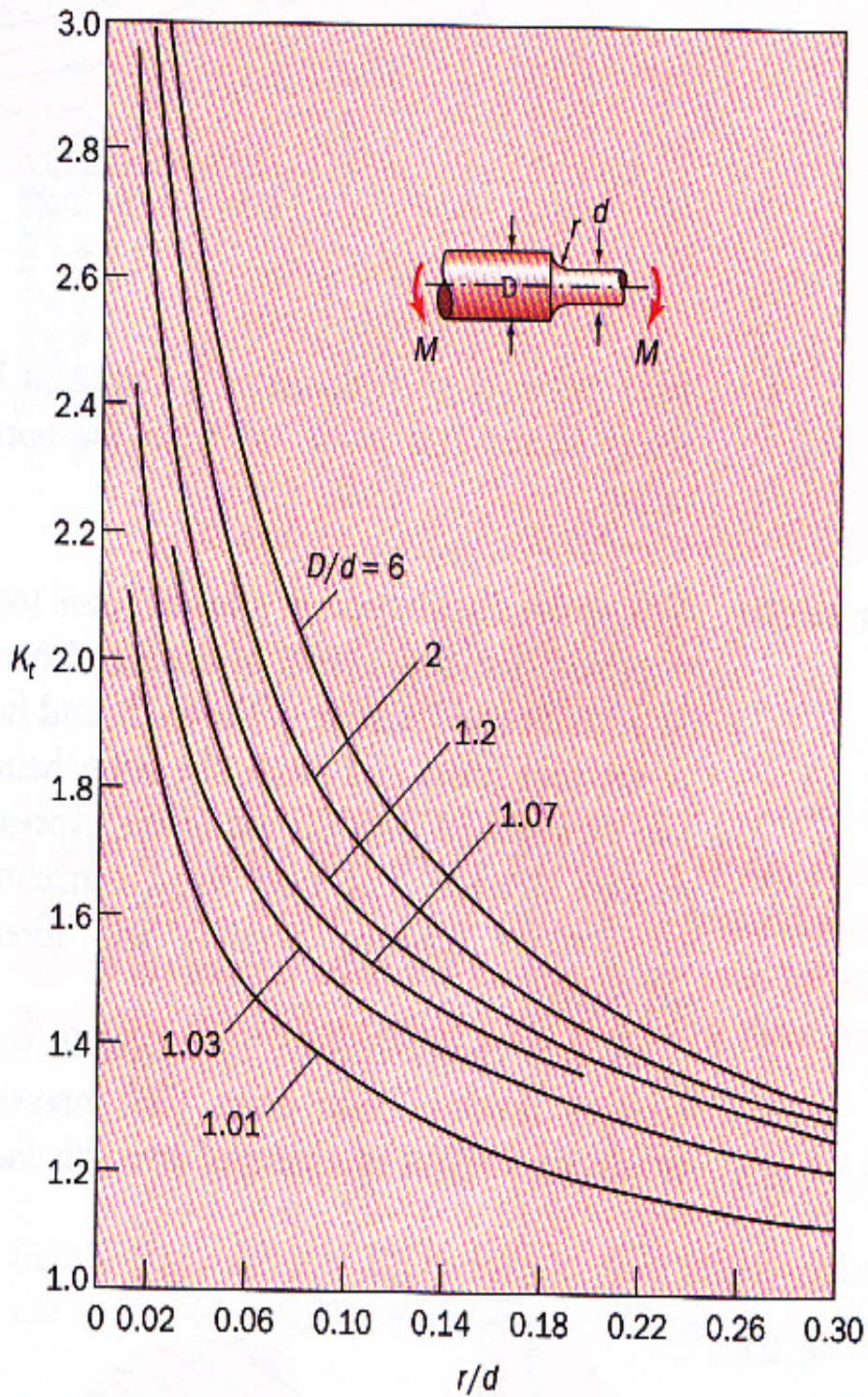
Selected Trigonometric identities	Selected Trigonometric integrals
$\sin^2 \theta = \frac{1}{2}(1 - \cos 2\theta)$	$\int \sin x dx = -\cos x + c$
$\cos^2 \theta = \frac{1}{2}(1 + \cos 2\theta)$	$\int \cos x dx = \sin x + c$
$\sin \theta \cos \theta = \frac{1}{2} \sin 2\theta$	

### Selected formulas for stresses for pressurized systems

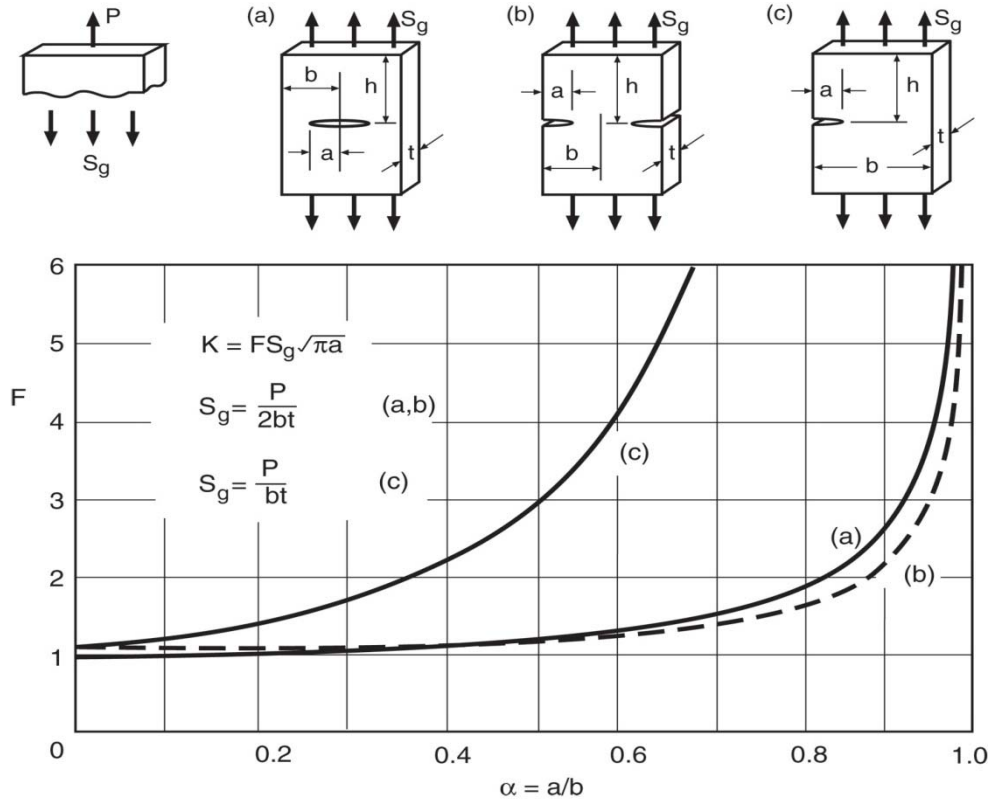
Hoop stress:	$\sigma_H = \frac{pr}{t}$	for relatively thin wall vessel
Longitudinal stress:	$\sigma_L = \frac{pr}{2t}$	for relatively thin wall vessel
Hoop and Longitudinal stress	$\sigma_H = \sigma_L = \frac{pr}{t}$	for relatively thin spherical vessel

For use in Q3[a]

Stress concentration factor  $K_t$  for the bending of a shaft with a shoulder fillet



For use in Q3[b]



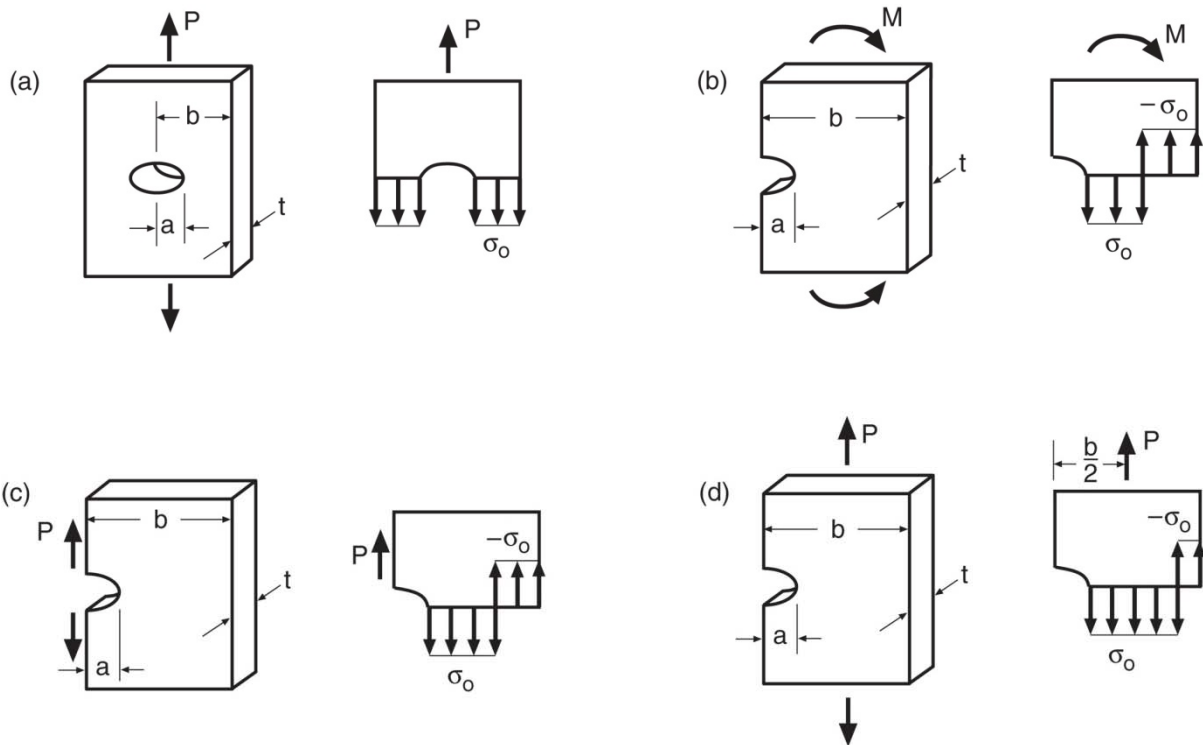
Irwin's Equation

(i)	$K_I = FS\sqrt{\pi a}$	$F \propto \frac{a}{b}$
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Expression for K-Calibration factors

(a)	$F = \frac{1 - 0.5\alpha + 0.326\alpha^2}{\sqrt{1 - \alpha}}$	$\left(\frac{h}{b} \geq 1.5\right)$
(b)	$F = \left(1 + 0.122 \cos^4 \frac{\pi\alpha}{2}\right) \sqrt{\left(\frac{2}{\pi\alpha} \tan \left(\frac{\pi\alpha}{2}\right)\right)}$	$\left(\frac{h}{b} \geq 2\right)$
(c)	$F = 0.265(1 - \alpha)^4 + \frac{0.857 + 0.265\alpha}{(1 - \alpha)^{3/2}}$	$\left(\frac{h}{b} \geq 1\right)$

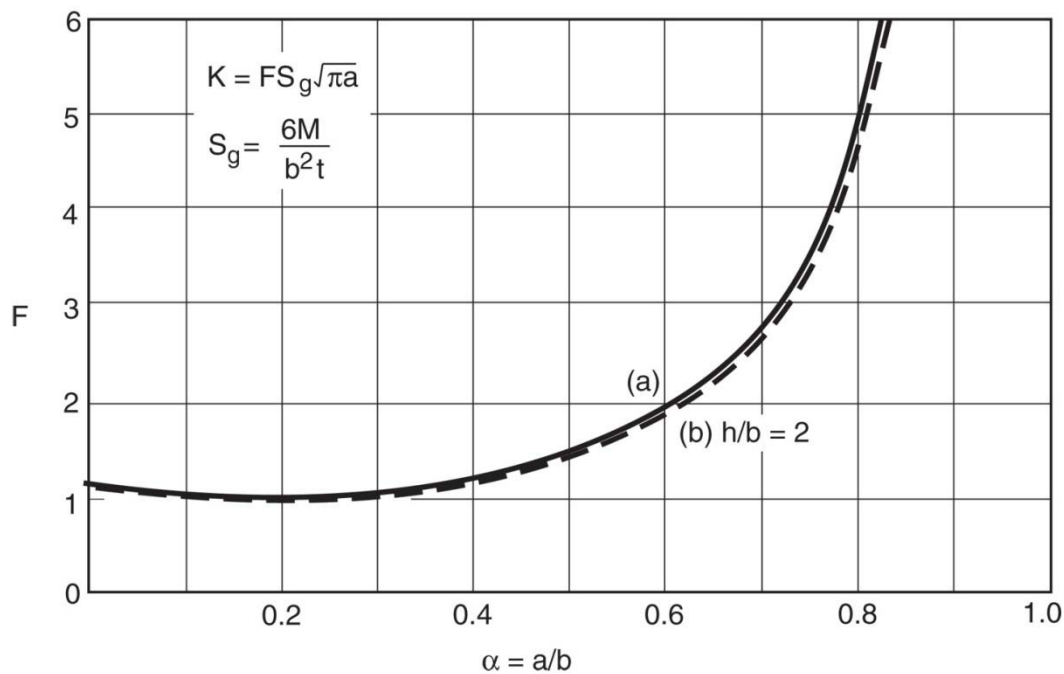
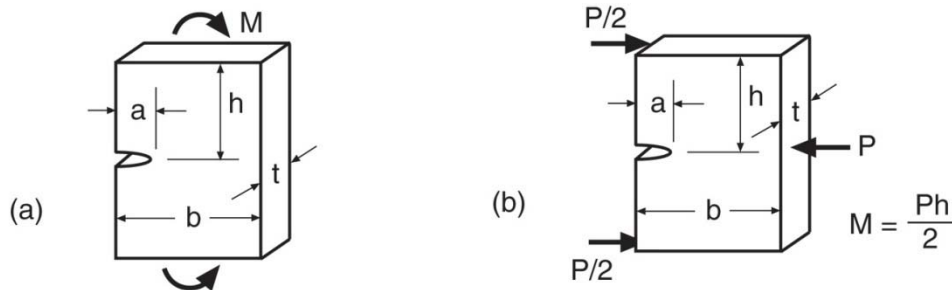
For use in Q3[b]



Fully plastic force or moment for given  $a/b$  :

(a)	$P_o = 2bt\sigma_o(1 - \alpha)$
(b)	$M_o = \frac{b^2t\sigma_o}{4}(1 - \alpha)^2$
(c)	$P_o = bt\sigma_o \left[ -\alpha - 1 + \sqrt{2(1 + \alpha^2)} \right]$
(d)	$P_o = bt\sigma_o \left[ -\alpha + \sqrt{2\alpha^2 - 2\alpha + 1} \right]$

For use in Q4[a]



**Expression for K-Calibration factors**

(a)	$F = \sqrt{\frac{2}{\pi\alpha} \tan\left(\frac{\pi\alpha}{2}\right)} \left[ \frac{0.923 + 0.199 \left(1 - \sin\frac{\pi\alpha}{2}\right)^4}{\cos\left(\frac{\pi\alpha}{2}\right)} \right]$	<p>Large <math>\frac{h}{b}</math></p>
(b)	<p>F is within 3% of (a) for <math>h/b = 4</math>, and within 6% for <math>h/b = 2</math>, at any <math>a/b</math>:</p> $F = \frac{[1.99 - \alpha(1 - \alpha)(2.15 - 3.93\alpha + 2.7\alpha^2)]}{\sqrt{\pi}(1 + 2\alpha)(1 - \alpha)^{3/2}}$	<p><math>\left(\frac{h}{b} = 2\right)</math></p>

## APPENDIX 6/LAMPIRAN 6

For use in Q5[b]

Secondary stage creep law :

(i)	$\dot{\epsilon} = B\sigma_e^{n-1}$
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