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Effects of Increasing Load Transferred in Femur to the Bone-Implant Interface

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Abstract: This study explores the phenomenon by identifying the causes of stress shielding and some of the factors, which may reduce its effect on the femoral bone. There are several factors that influence stress shielding including the designs of implant stem geometry and the chosen of an implant material. These two factors can be mathematically proved by identifying how load was transferred in composite material. For this matter, only axial load was taken into account. The effects at bone/cement and cement/stem interfaces and force due to bending will be also considered.

Key words: Hip prosthesis, load transfer, stress shielding, interface

INTRODUCTION

For the past few decades, various studies in hip replacement joint have been carried out in order to improve the performance of hip implant. Most of them were trying to make the artificial joint behaves like the normal joint. Design aspects like stem-bone bonding, the most suitable implant material and shapes, the stability of the implant inside the femur and bone reaction along interface etc have been given the greatest consideration.

The hip joint can fracture and damage due to various reasons such as involving in road accident, falling down stairs, osteoporosis, or disease that affects joint tissue like rheumatoid arthritis. The hip fracture is a serious injury that can occur to anybody. Buford and Gosawami[1] mentioned that, in a year 2000 alone, almost 11% from 500,000 operations were performed in The United States of America for patients aged within 40 years. Hip fracture can lead to permanent disability, pneumonia, pulmonary embolism and death. Worldwide, Keyak and Falkinstein[2] stated that, the numbers of hip fractures are expected to increase to over 6.26 million in the year 2050.

Most of the patients with fracture hip experience difficulty in doing their routine activities. Consequently, they require hip replacement or arthroplasty to overcome this difficulty[3]. A hip replacement is a procedure of replacing the diseased hip joint with a new artificial part called prosthesis. It is used to transfer load from the acetabulum to the femur through a metal stem that is inserted into the femur[4]. The procedure is aimed to relieve the pain and improve mobility.

Although patients will be able to return and enjoy their activity even not as active as before the operation, the possibility for revision surgery still exists. The term revision surgery is used when replacing a previously replaced hip joint. Almost 10% from overall operations would undergo for revision surgery[5]. However this situation depends on patients' conditions and types of prosthesis that were used. For heavier patient and age 30 years old during the operation, nearly 33% of them will need to do the revision operation after 10 years.

Based on the research conducted by Malchau *et al.*[6], there were almost 20% of 10,000 operations made in Sweden would go for revisions which 7% from it used cemented femur and the other 13% used cementless design. The risk of revision operation is extremely high especially to elderly patients and its complications include cardiac problem, pulmonary problem and mortality[7]. Hence, the possibility for it to occur should be minimized.

Havelin *et al.*[8] also did the same survey in Norway from September 1987 to end of 1990 where the most common reasons for revisions were loosening of the stem, which contributed almost 64%. In other survey performed by Malchau *et al.*[9] in Sweden from 1987 to 1990, 79% of all revisions were due to implant loosening. Implant loosening is a mode of failure resulting from implant movement or migration in the bone or cement. The most common cause of implant loosening is the loss of bone mass due to stress shielding[10,11].

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Stress shielding in femur occurs when some of the loads are taken by prosthesis and shielded from going to the bone[5,12]. Normally, femur carries its external load by itself where the load is transmitted from the femoral head through the femoral neck to the cortical bone of the proximal femur. When prosthesis is introduced into the canal, it shares the load and the carrying capacity with bone. Originally, the load is carried by bone, but it is now carried by implant and bone. As a result, the bone is subjected to reduced stresses and hence stress shielded[10].

If is seen through x-ray film, there will be small gaps along bone/implant interface. Dual Energy X-ray of Absorptiometry (DEXA) is a widely used method for quantifying bone mass and Bone Mineral Density (BMD) at the lumbar spine, proximal femur, distal radius and other skeletal sites. Lozynsky *et al.*[13] quantified the Bone Mineral Content (BMC) and Bone Mineral Density (BMD) of proximal femur in autopsy retrieved from cemented femoral stems. DEXA radiographic analysis was used to quantify bone content and density in 13 femurs containing cemented implants with duration of 12-191 months. The proximal region had the greatest bone loss, on average 40%. McAuley[14] also reported that out of 426 patients that used cementless stem; on average 24% of them show loss of BMC.

All of these data proved that, there would be a reduction in volume of femur after hip replacement operation. The changes in bone's volume and mass will take a few years, as its reaction to outside environment is too slow[15]. However, after certain period of time, the implant will no longer stabilise in femur. Stress shielding reduces the support of the implant and therefore increases the risk of implant loosening. The effects from implant loosening and micromotion of prosthesis relative to femur can cause difficulties to patients whenever they do daily activities. If this situation continues, revision surgery will be most beneficial and likely to be carried out.

However, the bone around the removed femoral component has less bone stock. Therefore, the new implant needs to be longer and thicker so that it will be stabilised steadily in the bone. But, the same problem like stress shielding may occur. The new implant possibly works for another years until it will loose again and needs to be replaced. Normally, this process does not continuously occur. There must be some limit such as how many years as one can expect to keep a series of prostheses depends on patient's bone stock. After that, patient needs to consider bone grafting. Thus, after considering this entire problem, the phenomena like stress shielding must be eliminated.

MATERIALS AND METHODS

Composite beam theory: In order to reduce stress shielding problem, most of the loads that come from patient's weight and activities must be distributed to the bone. Three materials represented implant, cement and bone were bonded and equal axial force, F (N) was applied as given in Fig. 1. All of these materials consist of different value of Young modulus, E (GPa) and area, A (m^2). From this formulation, we can see a good relationship between the distributions of load to each material.

Then the strain in each bar must be equal:

$$\varepsilon = \varepsilon_1 = \varepsilon_2 = \varepsilon_3 \tag{1}$$

Using Hooke's law and also the fact that stress is force/area, then:

$$\frac{\sigma}{E} = \frac{\sigma_1}{E_1} = \frac{\sigma_2}{E_2} = \frac{\sigma_3}{E_3} \tag{2}$$

$$\frac{F}{AE} = \frac{F_1}{A_1E_1} = \frac{F_2}{A_2E_2} = \frac{F_3}{A_3E_3} \tag{3}$$

It was also known that deformation on parallel materials gives us Voight's model or the rule of mixtures,

$$E = \frac{1}{A}(A_1E_1 + A_2E_2 + A_3E_3) \tag{4}$$

Which when substituted Eq. 4 into 3, at last,

$$F_i = \frac{A_iE_iF}{A_iE_i + A_bE_b + A_cE_c} \tag{5}$$

$$F_c = \frac{A_cE_cF}{A_iE_i + A_bE_b + A_cE_c} \tag{6}$$

$$F_b = \frac{A_bE_bF}{A_iE_i + A_bE_b + A_cE_c} \tag{7}$$

Where, notation i for implant, c for cement and b for bone,

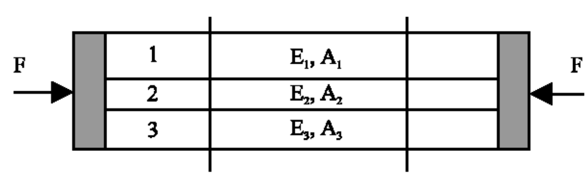

Fig. 1: Three different materials were bonded and subjected to an equal force compressed on them

From the three Eq. 5, 6 and 7 derived, there were two factors that affect transferring load in every materials, i.e., material stiffness and cross sectional area. If properties of bone and cement were fixed, the amount of transferring load would only depend on implant. Three materials were chosen for comparison purposes, i.e. Titanium (Ti), Cobalt Chromium (Co-Cr) and iso-elastic. Iso-elastic was chosen because it had modulus Young equal to bone. Meanwhile, Ti and Co-Cr were two materials that were commonly mentioned in literature[5,16-18]. These materials were analysed by varying its diameter. Mechanical properties for bone, cement and three different implant materials are shown in Table 1.

In order to see whether implant geometry have a strong impact on the distribution of load to bone (F_b/F), hence, two different types of stem would be analyzed here, i.e. solid and hollow stems.

Stress developed at interface: The stresses at interfaces were examined using commercial Finite Element (FE) package ANSYS 7.1. The analysis was carried out in 3-dimensions. For this purpose, iso-elastic was chosen as an implant material because it had demonstrated the highest transferring load in femur. Material properties used for FE were given in Table 1. The model was considered as cylinders and assumed homogenous, isotropic and linear elastic. The dimensions could be seen in front view as in Fig. 2a and in top view as in Fig. 2c and d. To ease the analysis, only half portions of surface were analysed, as shown in Fig. 2b.

For the case of solid stem, loads applied to the model were obtained from graphs in Fig. 3a-c. Whereas for

Table 1: Rigidity for bone, cement and three different implant materials[1]

Materials	Modulus Young, E (GPa)	Poisson's ratio (v)
Bone	20	0.3
Cement	2	0.3
Cobalt-Chromium (Co-Cr)	200	0.3
Titanium (Ti)	115	0.3
Iso-elastic (Iso)	20	0.3

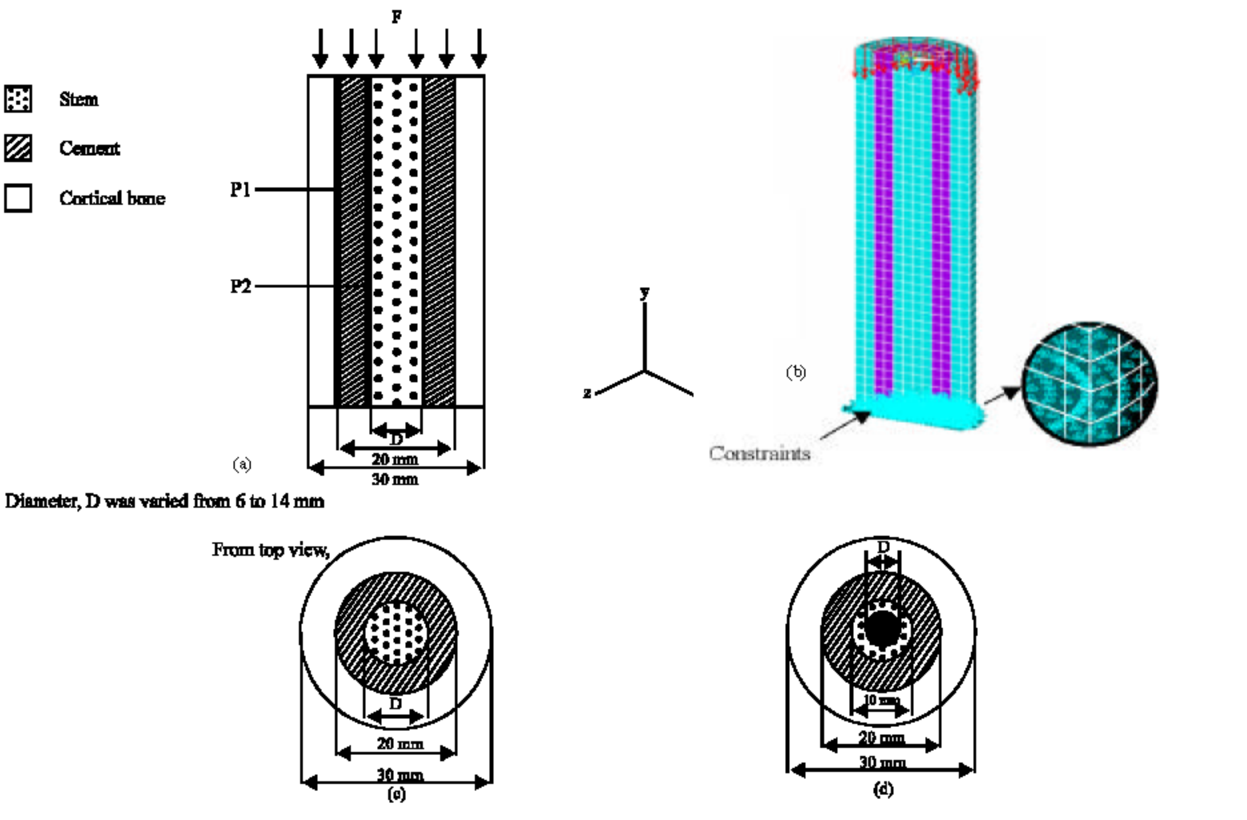

Fig. 2: (a) Diagram of the model showing dimensions and path locations. The length of the model is 120 mm. (b) Meshed finite element model showing loading and constraints. (c) Solid stem with varying diameter, D. (d) Hollow stem with D_i was varied from 2 to 9 mm

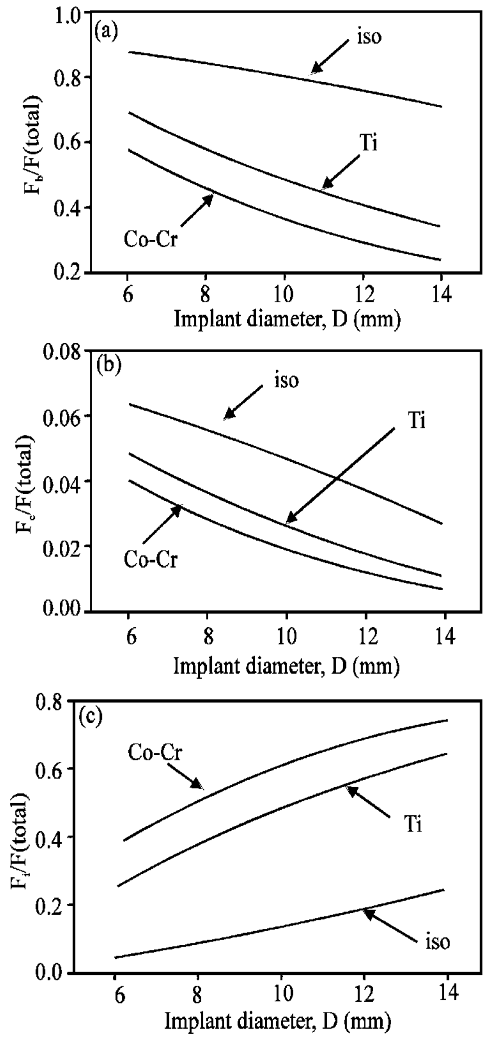

Fig. 3: Effects from different implant materials and diameter to ratio of transferred load in (a) femur, (b) cement and (c) implant that occur in solid stem

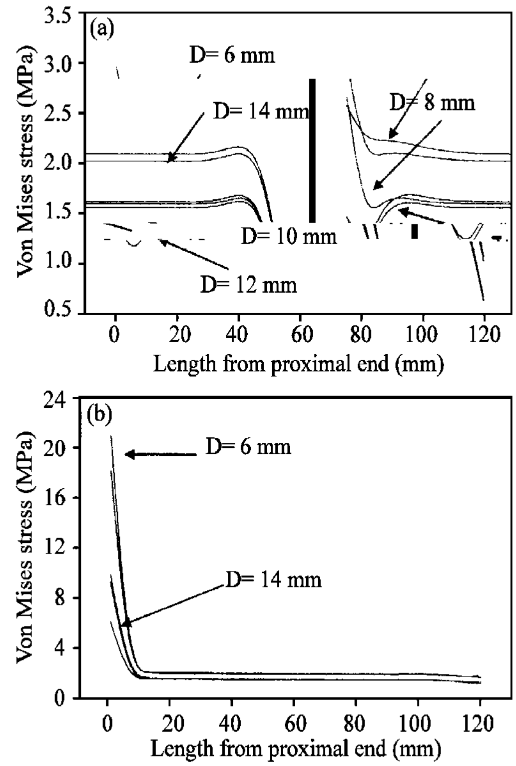

Fig. 4: Von Mises stresses along interface, for solid stem: (a) bone/cement (P1), (b) cement/implant (P2)

hollow stem, loads were taken from Fig. 5a-c. All loads were distributed at the proximal end of the model. No muscles forces had been taken into consideration.

The distal end of the model was rigidly fixed in x, y and z directions, that are $U_x = 0$, $U_y = 0$ and $U_z = 0$. The model was divided into several small elements of 3 mm length and the element type twenty node hexahedral finite elements (ANSYS type SOLID95) was used.

RESULTS AND DISCUSSION

Solid stem: If bone diameter was 30 mm and cement diameter was set to be 20 mm, whereas implant diameter, D, was varied between 6 to 14 mm, the effects from different implant materials to the ratio of transferred load can be plotted as in Fig. 3 (from Eq. 5-7).

Figure 3a-c showed that transferring load was dependent on selection of implant material. It was proven that material with lower stiffness could increase load transferred to bone. From the study carried out, it was seen that femur received more loads at every applied load when iso-elastic was the implant material, generating less bone resorption. For example, Table 2 shows that iso-elastic material with 10 mm stem diameter, F_b/F was about 0.79, there were a reduction of 43.04% in Ti and 58.23% in Co-Cr.

Besides, the effects between different stem diameters could also be evaluated from the same graph. (F_b/F) in iso-elastic was shown to decrease as much as 19.54% with

Table 2: Effects from different stem materials to F_b/F with 10 mm diameter (round up to two decimal points)

Stem materials	F_b/F	Percentage of decrease (%)
Iso-elastic (ref)	0.79	N/A
Ti	0.45	43.04
Co-Cr	0.33	58.23

Table 3: Effects from stem thickness to F_b/F (round up to two decimal points)

	F_b/F		
Stem materials	D = 6 mm (ref)	D = 14 mm	Percentage of decrease (%)
Iso-elastic	0.87	0.70	19.54
Ti	0.67	0.30	55.22
Co-Cr	0.56	0.20	64.29

Table 4: Percentages of increases in stress at interface occurred in different stem diameters

Stem description	P1 (MPa)	Percentage of increase (%)	P2 (MPa)	Percentage of increase (%)
D = 14 mm (ref)	2.63	N/A	6.14	N/A
D = 12 mm	1.63	-36.02	9.30	51.47
D = 10 mm	1.68	-36.12	9.80	59.61
D = 8 mm	2.55	-3.04	18.10	194.79
D = 6 mm	2.97	12.93	20.86	239.74

Table 5: Effects from hollow stem to F_b/F (round up to two decimal points)

	F_b/F		
Stem materials	Solid 10 mm D (ref)	Hollow, 10 mm OD, 9 mm ID	Percentage of increase (%)
Iso-elastic	0.79	0.91	15.19
Ti	0.45	0.78	73.33
Co-Cr	0.33	0.69	109.10

an increasing in implant diameter from 6 to 14 mm, compared to Ti (55.22%) and Co-Cr (64.29%) (Table 3). It proved that, for all materials studied, thin stem took less loads when compared to thick stem. In Fig. 3a and b, we could see that all graphs were descending. In contrast, Fig. 3c showed the rise of load in prosthesis for the thicker stem diameter. In conclusion, to increase F_b/F, thinner implant with low Young modulus will be the right choice.

Figure 4a and b illustrated that most of the stress lay near the proximal end and decreasing towards the distal end. However, thinner stems produced higher stress at cement/implant interface (Table 4). For implant with 6 mm diameter, the maximum stress might increase until up to more than 200% compared with 14 mm implant diameter. Femur received larger amount of load when stem diameter was smaller and the stress at cement/implant interface was much higher as compared to stress at bone/cement interface.

Hollow stem: In this section, bone and cement diameter were similarly set as solid stem. Implant outer diameter, OD, was chosen as 10 mm and its inner diameter, ID, was varied from 1 to 9 mm. Effects from hollow stem to ratio of transferred load was plotted as in Fig. 5.

The values of F_b/F and F_c/F had a positive relation with the value of implant inner diameter as showed in

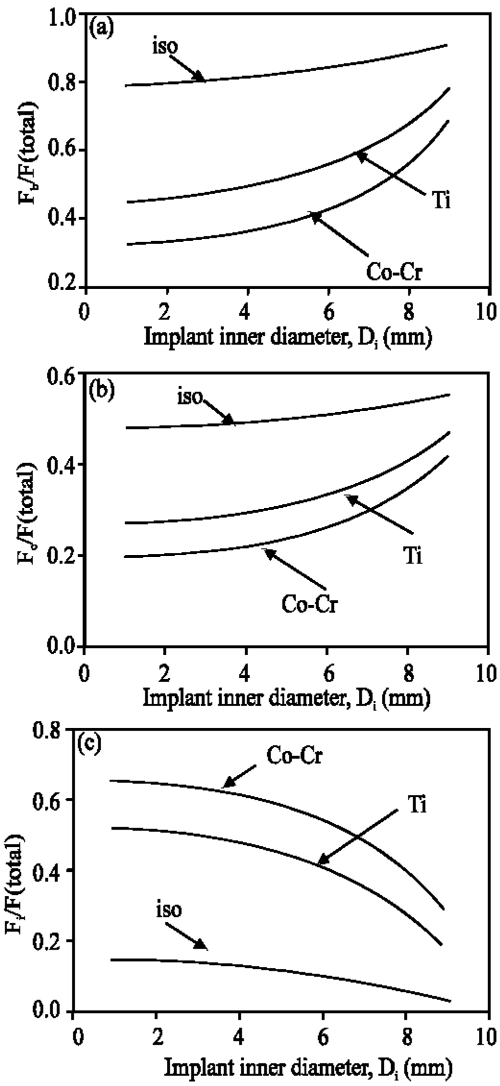

Fig. 5: Effects from different implant materials and diameter to ratio of transferred load in (a) femur, (b) cement and (c) implant that occur in hollow stem

Fig. 5a and b. For hollow implant with outside diameter was 10 mm, F_b/F would be increased by increasing inner diameter. It also verified that, F_b/F of hollow stem increased higher than solid stem.

In Fig. 5a-c, all lines seemed to get close to each other especially when ID was 9 mm and developed small differences among those values. F_b/F in iso-elastic was 15.19% higher compared to when in solid stem, whereas Ti (73.33% higher) and Co-Cr (109.10% higher) (Table 5).

Table 6: Percentages of increases in stress at interface occurred in hollow stem with different inside diameters

Stem description	P1 (MPa)	Percentage of increase (%)	P2 (MPa)	Percentage of increase (%)
Solid, 10 mm D (ref)	1.68	N/A	9.80	N/A
Hollow, 10 mm OD, 2 mm ID	3.20	90.48	9.90	1.02
Hollow, 10 mm OD, 4 mm ID	3.40	102.38	10.00	2.04
Hollow, 10 mm OD, 6 mm ID	3.51	108.99	10.10	3.06
Hollow, 10 mm OD, 8 mm ID	3.64	116.61	10.42	6.31
Hollow, 10 mm OD, 9 mm ID	3.89	181.67	11.67	19.06

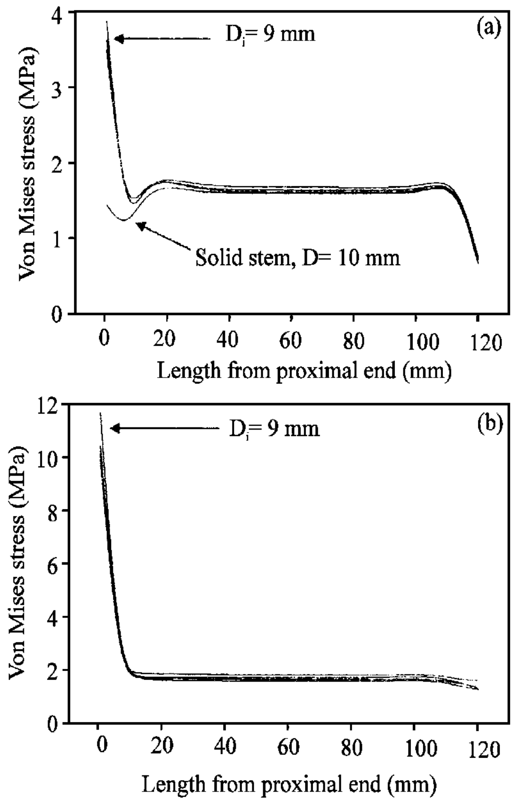

Fig. 6: Von Mises stresses along interfac, for hollow stem, (a) bone/cement (P1), (b) cement/implant (P2)

The same value of F_b/F could be attained either in solid or hollow stems since it was dependent on area. For example, solid stem made of Titanium with 6 mm in diameter would have same F_b/F with hollow stem that had 10 mm outer diameter and 8 mm inner diameter.

Figure 6a and b also illustrated that most of the stress lay near the proximal end and decreasing towards the distal end. One interesting fact to see is the value of stresses could develop differently at interfaces although with a same value of F_b/F. For example, the stress produced in hollow stem with 10 mm outer diameter and 8 mm inner diameter was found not more than 11 MPa (Table 6). However, in solid stem with similar area that is 6 mm outer diameter produced higher stress which was more than 20 MPa as shown in Fig. 6b. The differences in stress were probably due to higher value of F_c/F (25%) in solid stem compared to hollow stem.

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