Material Selection for Axial Spring in a Prototype Cam-Follower Mechanism

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Authors’ contributions

This work was carried out in collaboration between all authors. Author KJA designed the study, performed the modeling and CES EduPack selection analysis, wrote the protocol and wrote the first draft of the manuscript. Authors GEO, OTB and ATT did the Pro-E analysis, literature searches and data analysis respectively. Authors ARA and OOA supervised the study and interpreted the results. All authors read and approved the final manuscript.

ABSTRACT

A prototype cam-follower mechanism was designed and assembled using Pro-Engineer (Pro-E) software. The mechanism is meant for application in a forth-and-back Mode II Operation of a tribotester rig. The mechanism was dynamically simulated in Pro-E to ascertain the dynamic loading status of integral parts. CES EduPack software was applied to select the best material for the spring using the Function-Objectives-Constraints approach. Candidate materials were first screened using design constraints after which shortlisted materials were ranked using design objectives. The final material choice made with reasonable trade-offs was found suitable for intended service environment requirements.

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1. INTRODUCTION

Originally, man had access to a limited number of materials which he could use directly or after a few steps of traditional processing. The development of materials has come through a long way in mankind’s history. Today, man has at his disposal tens of thousands of materials which have been metallurgically and/or chemically processed [1]. Nowadays, the evolution of new and emerging materials is so overwhelming that mankind’s problem has moved far away from insufficient supply of materials to that of selecting the best material from amongst a myriad of seemingly suitable materials!

Essentially, the task of selection is that of matching the choice of material to the requirements of the design [2,3]. Novel or well selected materials provide designers with excellent features. For instance, new materials offer promising perspectives in assisting automotive engineers to achieve improvement in vehicle fuel efficiency [4].

Nowadays that classification has become more complex, materials selection process is more elaborate with large collections of material groups having been bundled together into databases and charts. Better still, a lot of high performance research software has been developed with electronic capacity to surf and peruse extensive databases, make intelligent choices and complement analytical structural simulations. The CES material and process selection software is an example of such a computer implementation [2]. Other analytical techniques may also be adopted for various designs [5,6]. In the present work, CES EduPack [7] is applied to select the material for a cam-follower mechanism for application in a tribotester.

2. METHODOLOGY

2.1 Design and Function

The prototype cam-follower mechanism was designed and assembled using Pro-Engineer (Pro-E) software. The mechanism was dynamically simulated in Pro-E to ascertain the loading status of each part. Figs. 4, 5 and 6 show the dynamic loading states at limit frames as captured in Pro-E. CES EduPack was applied to select materials for the spring using the Function-Objectives-Constraints approach. The mechanism is intended for application in the Mode II function of a tribotester for determining the adhesive wear resistance of solid materials subjected to a forth-and-back fretting motion. The specific function of a spring is that of storing potential elastic energy and releasing it when needed.

2.2 Constraints and Objective

Constraints represent crucial non-negotiable design conditions to be met. Constraints for the design of the spring are: No failure by fatigue; fracture toughness higher than 1E7 Pa.m\(^{1/2}\) and cost not beyond 10 USD/Kg. Technical constraints were deduced from dynamic simulation while cost constraint is an administrative decision. Objectives represent what the

\footnote{CES EduPack is a trademark of Granta Design Limited—the software used to create the charts and property rankings used in this paper.}
design is required to maximize, minimize or maintain in its function. Accordingly, the spring is required to store maximum potential energy and release it when needed.

2.3 Screening and Ranking

The elastic energy [2] stored per unit volume in a piece of material stressed uniformly to a stress \( \sigma \) is given by:

\[
\psi_v = \frac{1}{2} \frac{\sigma^2}{E}
\]  

(1)

where \( E \) is the Young’s Modulus. Then:

Material index

\[
M_1 = K \frac{\sigma^2}{E}
\]  

(2)

where \( K \) is a numerical constant. \( K \) has no influence on the choice of material.

Suppose that the axial spring will be damaged if \( \sigma \) exceeds the failure stress \( \sigma_f \) (then \( \sigma_f \) becomes the fatigue strength since the Pro-E dynamics simulation of the prototype mechanism shows a cyclic loading for the spring). The best material for springs, irrespective of the way in which they are loaded, is that with the biggest value of \( M_1 \).

The logarithmic form of the objective function can be expressed in the standard equation of a straight line as

\[
\log \sigma_f = \frac{1}{2} \log E + \frac{1}{2} \log M_1
\]  

(3)

Fig. 1 is a plot of this equation in CES EduPack where \( M_1 \) has a slope of 0.5. Figs. 2 and 3 show screening using the design constraints.

Ranking was done to arrange materials that survived screening in a definite order. This order principally shows which material can do the job best.

3. RESULTS AND DISCUSSION

For the purpose of this application where preference is given for high modulus, all material families other than steel were screened off. The selection collection now parades stainless steel, alloy steel, high carbon steel and medium carbon steel. Ranking was done on the basis of performance index, Fig. 7 (which embodies fatigue strength and Young’s modulus), fracture toughness, Fig. 8 and cost, Fig. 9. The results and consideration for selection are tabulated in Table 1. The ranking stages as obtained from CES EduPack selection panes are shown in Figs. 7, 8 and 9. The final material selected is high carbon steel. High carbon steel has the second highest performance index, second highest fracture toughness and is the second cheapest. The choice of high carbon steel maximizes performance while minimizing cost. In metallurgical practice, high carbon steel when quenched and tempered, has very high hardness, wear resistance and springiness.
Fig. 1. Fatigue strength as a function of Young’s modulus (CES EduPack 2008)

Fig. 2. Fracture toughness as a function of price (CES EduPack 2008)
Fig. 3. Young’s modulus as a function of Price (CES EduPack 2008)

Fig. 4. No load frame (Cam position when spring is not loaded)
Fig. 5. Peak load frame (Cam position when spring carries maximum load)

Fig. 6. Least load frame (Cam position when spring is lightly loaded)
Fig. 7. Ranking based on performance index (The higher the value of Index the better the ability of material to perform the function of a spring; hence for metals, Low alloy steel can perform best while Medium carbon steel can perform least)

Fig. 8. Ranking based on fracture toughness (Regarding maximum fracture toughness, medium carbon steel has lowest value while stainless steel has the highest value)

Fig. 9. Ranking based on price (Price increases from medium carbon steel-cheapest-to stainless steel-costliest)
Table 1. Selection consideration for shortlisted materials (Based on Figs. 4, 5 and 6)

| Material            | Strength                                      | Comment                                                                 |
|---------------------|-----------------------------------------------|-------------------------------------------------------------------------|
| Medium carbon steel | Lowest cost (cheapest)                        | Inadequate performance index and fracture toughness                     |
| Low alloy steel     | Highest performance index and adequate fracture toughness | Cost is relatively high (third cheapest)                               |
| Stainless steel     | Highest fracture toughness                    | Inadequate performance index and exorbitant cost                       |
| High carbon steel   | Second highest performance index and fracture toughness; second cheapest | Satisfies conditions for selection.                                     |

4. CONCLUSION

The study concluded that high carbon steel is the material choice that maximizes performance and minimizes cost for axial springs in applications whose service requirements are bounded by the stated constraints.

In general, cost is such an important factor that constrains most engineering designs and limits materials choice. CES EduPack has a flexible in-built capacity to involve cost as a general-purpose constraint in materials selection.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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