Precision & Performance Conference 2025, Cranfield University, UK, 17th- 20th November 2025

Study on the thermal stability of cold forged carbon fibre-based structural member for high dynamic machinery applications

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Abstract

Structural components in high dynamic machines such as industrial robots are typically made from structural steel, aluminium alloys or cast iron, and play a vital part in ensuring precision, load capacity and dynamic characteristics. These machines are widely used for material handling, machining, assembly and other processes like welding, painting, etc. However, these structures are susceptible to thermal distortion, which can affect accuracy and medium – term repeatability. There is a motivation to replace moving structures made from these traditional materials to lightweight structures manufactured using more sustainable methods. In this work, a structural member prototype was manufactured with carbon fibre tubes using a cold forging-based method. This prototype was tested for thermal stability using a high-accuracy Coordinate Measuring Machine (CMM) to measure dimensional change as a response to various thermal perturbations . The Coefficient of Thermal Expansion (CTE) of the prototype was calculated to be 3.4 ± 0.1 µm/m.°C which is 71% less than the structural steel-based structure. The prototype is able to provide high thermal stability, with anticipated high dynamic stiffness without compromising strength-to-weight ratio, making it ideal for applications like robot links, where both precision and stiffness are critical.

Cold forged carbon fibre composite, Thermally stable robot link, Multi-material structural member

1. Introduction

In the present engineering applications, such as in precision metrology, manufacturing and automation, there is an increasing demand for structural members that can provide high dynamic stiffness with reduced weight, while maintaining a high degree of thermal stability. One of the prominent examples is robots, which are widely used in manufacturing, where their repeatability is essential. These robots find applications in material handling, machining, assembly, and inspection. They are typically constructed from structural steel, cast iron, or aluminium alloys [1]. Industry and academia have shown a strong desire to use them in precision machining applications, pushing the accuracy performance beyond the limits that were originally intended.

In some cases, these machines are installed in workshops that are not temperature-controlled and may be located near significant heat sources or generate their own heat from friction in the drive train. Such temperature fluctuations can affect the dimensions of machine structures, for example, robot links. These links may expand or contract depending on the temperature they are exposed to, which can significantly impact the robot's accuracy and medium-term precision[2, 3].

Another critical aspect of design is the stiffness-to-weight ratio. It is generally desirable to minimise weight while maintaining high stiffness. Reducing the weight of the robot links offers several advantages, such as: improved acceleration and deceleration; reduced energy consumption; reduction in internally-generated heat; reduced constraint on foundations and mounting; improved portability and reconfigurability; etc. Additionally, manufacturing robot links using conventional materials often involves processes like casting, which are heat-intensive. These methods may reduce environmental sustainability and require specialised equipment and resources. Due to its high strength-to-weight ratio, excellent fatigue resistance and other mechanical properties, carbon fibre composite can be an alternative material option. However, a single thick Carbon Fibre Reinforced Polymer (CFRP) tube is also not feasible as a solution, as they are commercially uncommon and are susceptible to defects like porosity, fibre misalignment, incomplete curing, and associated costs.

This motivated the investigation of thermally stable structural components in dynamic applications like robot links that are both lightweight and stiff, utilising sustainable manufacturing methods. Building upon the concept design of the robot link [4], a prototype was manufactured using readily available carbon fibre tubes through a cold forging technique [5]. The CFRP tubes were arranged, as depicted in figure 1, and the space between them was filled with chopped carbon fibre epoxy composite. In this work, the prototype was tested for its thermal stability and compared with traditional materials commonly used in the manufacturing of robot links. Several research studies have focused on the thermal stability of CFRP composites using different methods; however, they do not address the thermal expansion behaviour of cold forged carbon composites or specifically, a multi-material structural member manufactured using this technique.

The thermal expansions are typically measured using methods like dilatometry, interferometry, and thermo-mechanical analysis. However, due to dimensional constraints, the use of dilatometry and interferometry is limited—particularly when the prototype is long and has a large diameter. Thermo-mechanical analysis also presents limitations related to sample dimensions and the precision required in sample shape. Salma et al. [6, 7] used a CMM to measure the thermal expansion of a CFRP tube. The CFRP was enclosed in a heated casing and CMM probing was carried out. ZERODUR® was used as the reference for the measurement. But since the prototype was fixed with embedded sensors based on optical fibres, this restricts the use of closed heating, as it can adversely affect the sensor performance.

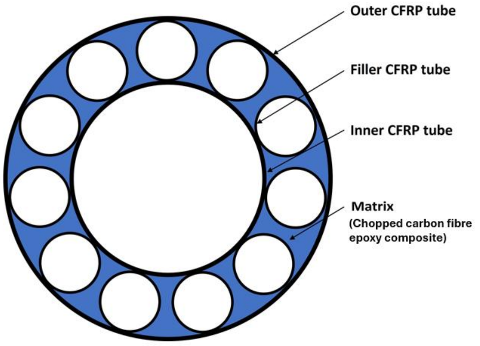


Figure 1. Modified John et al. [4] design of prototype

Due to the simplicity of the measurement procedure and the ability to accommodate a large prototype, this approach was considered feasible for the thermal testing. However, heating remained a challenge. In this research, the CMM room was heated, and error compensation was applied to determine the CTE of the developed prototype.

2. Methodology

Determining the thermal expansion of carbon fibre-based structures is difficult due to their low coefficient of thermal expansion. In this method, a CMM is employed to determine the deviation in length due to changes in temperature. Temperature deviations also affect the accuracy of the CMM measurements. To ensure precise measurement, a ZERODUR® rod measuring approximately 604 mm × 10 mm × 10 mm was used as the reference. ZERODUR® is an inorganic, non-porous ceramic material well known for its extremely low thermal expansion coefficient, typically in the range of 0.01 µm/m.°C [8]. Due to this extremely low thermal expansion, any observed change in its dimensions can be assumed to be errors in the measuring device when the reference is placed in the same environment. This relative measurement between the reference and the prototype length forms the methodological basis of this experiment.

2.1. Experiment set-up

The prototype and the reference ZERODUR® rod were placed on the granite bed of the CMM. The experiment was conducted in a temperature-controlled room. The prototype was fitted with three sensors on the CFRP section and two on the aluminium base as shown in figure 2. DS18B20 temperature sensors were employed for temperature measurement due to their accuracy and single-wire communication protocol, which allows multiple sensor connections to the same bus [9]. The total length of the prototype is 609 mm, while the aluminium base is 20 mm thick. The prototype was placed on two V-blocks to ensure equal heating by enabling the air circulation to all the areas.

2.2. Experiment procedure

The CMM measured several points on the top and bottom of the reference and then proceeded to measure the top and bottom of the test setup. The top surface of the aluminium base was also measured to separate the length of the prototype from the total setup length. The datum for the measurement was set at the top of the prototype. The CMM continuously measured these points, with a delay of a few minutes between each measurement cycle.

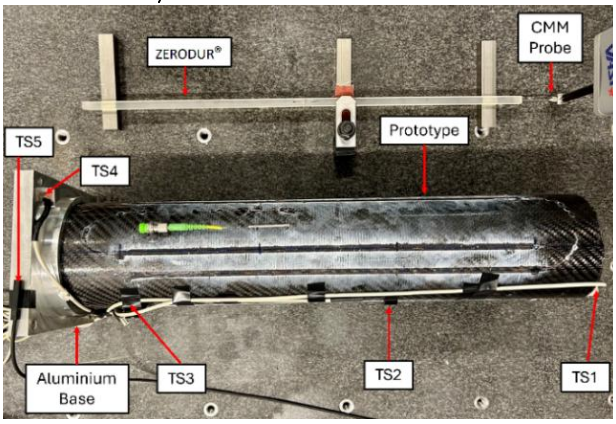


Figure 2. Test setup

The room temperature was changed using the centralised control system. The prototype was maintained at room temperature for 24 hours before starting the experiment. The sensors installed on the test setup monitored the actual temperature to which the prototype was exposed. The ambient room temperature was varied from 20.8°C to 28°C, as indicated by the control system. The upper set temperature was selected based on the heating limitations of the room. The temperature was maintained until the expansion readings reached a nearly constant value. After stabilising the prototype at elevated temperature, the temperature was reduced back to the room temperature (20.8°C). The temperature setting is illustrated in figure 3.

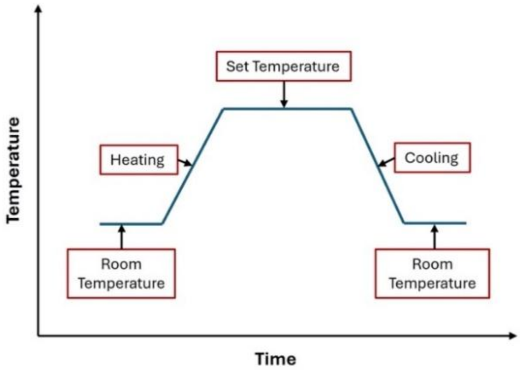
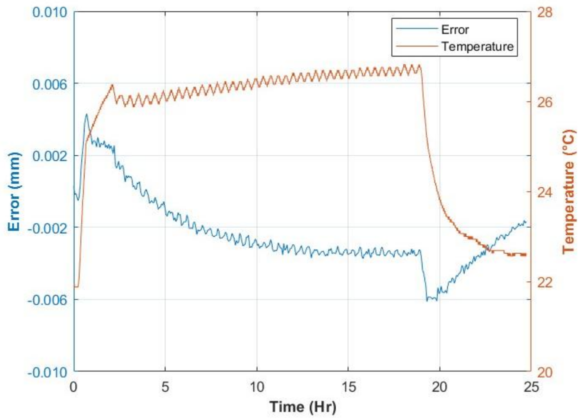


Figure 3. Temperature setting for the thermal test

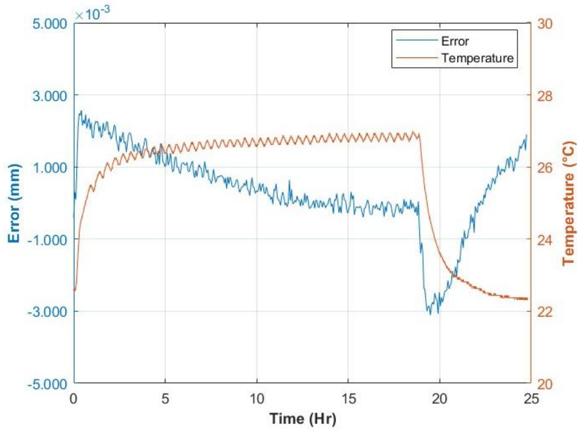
3. Results and Discussion

The results suggested that the CMM was expanding or contracting in accordance with the temperature, leading to the incorrect measurements of the reference's dimensions. The deviation in the length of the reference compared to its measurement at room temperature across the two tests is depicted in figure 4.

Based on the plots, both figure 4 a) and b) illustrate a similar trend. The CMM, being manufactured from various materials, expands unevenly when the temperature increases. The axis scales and structure undergo thermal expansion and deformation, leading to an increase in the measured length of the reference. Over time, the measured length reduces and gradually becomes nearly constant as the machine stabilises at the set temperature, which is evident from the graph. The operating conditions far exceed the specification for the CMM, so it is understandable that the thermal compensation system on the machine may not fully compensate. When the temperature is reduced, the opposite trend was observed.



a)



b)

Figure 4. Deviation in the reference length compared to its length at room temperature for: a) test 1 and b) test 2

The temperature fluctuations in the stable region correspond to the effect of the air conditioning feedback system. When the set temperature is reached, the centralised air conditioning system turns off until the temperature drops to the minimum threshold, triggering the system to turn on again. This cycling causes the wavy pattern observed in the temperature plots.

Figure 5 a) and b) depict the length of the complete test set up, measured over a span of about 25 hours. The plots also incorporated the temperature measured from the prototype surface. These plots are based on the direct values obtained from the CMM, which did not completely mimic the shape of the temperature profile. The regions where the trend diverged are marked in the plots. The error, measured from the reference, was then discounted and filtered to produce figure 5 c) and d) corresponding to test 1 and test 2, respectively. These corrected plots depict the hysteresis behaviour of the prototype manufactured using the cold forging technique.

The thermal expansion coefficient of the experimental setup was determined from both the heating and cooling cycles using the equation (1):

$$\text{CTE}, \alpha = \frac{\Delta L}{L \Delta T} \quad (1)$$

where:
α: Coefficient of Thermal Expansion, $°C^{-1}$
ΔL: change in sample length, mm
L: original sample length, mm
ΔT: change in temperature, ℃

The stable region from the graphs was extracted to obtain the thermal expansion at the set temperature. The coefficient of thermal expansion of the test set-up was calculated from both heating and cooling phases, represented in table 1.

Table 1. Coefficient of Thermal Expansion

Test	CTE	Total set-up	Prototype
Test 1	Heating	5.21 µm/m.°C	3.55 µm/m.°C
	Cooling	5.16 µm/m.°C	3.31 µm/m.°C
Test 2	Heating	5.16 µm/m.°C	3.35 µm/m.°C
	Cooling	5.37 µm/m.°C	3.47 µm/m.°C

The average expansion of the total test set-up was estimated to be 5.2 µm/m.°C and includes the contribution of the aluminium base, which was bolted to the prototype. From the analysis it is evident that the range of CTE is minimal, with a calculated value of 0.2 µm/m.°C. The expansion of the aluminium base over the temperature range was measured and subtracted from the total setup length. This resulted in the length of the prototype, with measurement error. The obtained error was then removed to isolate the true length variation of the prototype in response to temperature changes. Based on the stable regions, the average thermal expansion coefficient of the prototype was calculated to be 3.4 ± 0.1 µm/m.°C

The prototype consisted of CFRP tubes, carbon fibre epoxy material as the gap fillers, and aluminium plugs to connect it to the robot joint. Usually, the CTE of CFRP tube composite is typically around 1.5 µm/m.°C, whereas the filler matrix material, constituted of chopped carbon fibre and epoxy, may have a higher CTE value due to the lack of fibre alignment and the higher CTE value of the epoxy resin. This altogether forms a complex system, whose coefficient of thermal expansion was determined through this experiment.

Table 2. Comparison of Coefficient of Thermal Expansions [10, 11]

Material	Coefficient of Thermal Expansion
Prototype	3.4 µm/m.°C
CFRP tube	1.5 µm/m.°C
Structural steel	11.7 µm/m.°C
Aluminium alloy	23.4 µm/m.°C
Grey Cast iron	10.4 µm/m.°C

The obtained coefficient of thermal expansion of the prototype must be compared to the traditional material's CTE values in order to draw conclusive evidence that the new concept design is thermally more stable than links manufactured from conventional materials. The comparison of the coefficient of thermal expansion with the traditional material is presented in the table 2. There is an approximate 71% reduction in CTE compared to a structural steel-based component, and the reduction increases to about 86% when compared with an aluminium alloy. A substantial reduction of approximately 67% is also observed in comparison with grey cast iron. These findings suggest that the prototype offers an effective and thermally stable solution, with the potential to enhance the accuracy of precision manufacturing machines.

3. Conclusion

The prototype structural element was manufactured with commercially available CFRP tubes using a sustainable cold

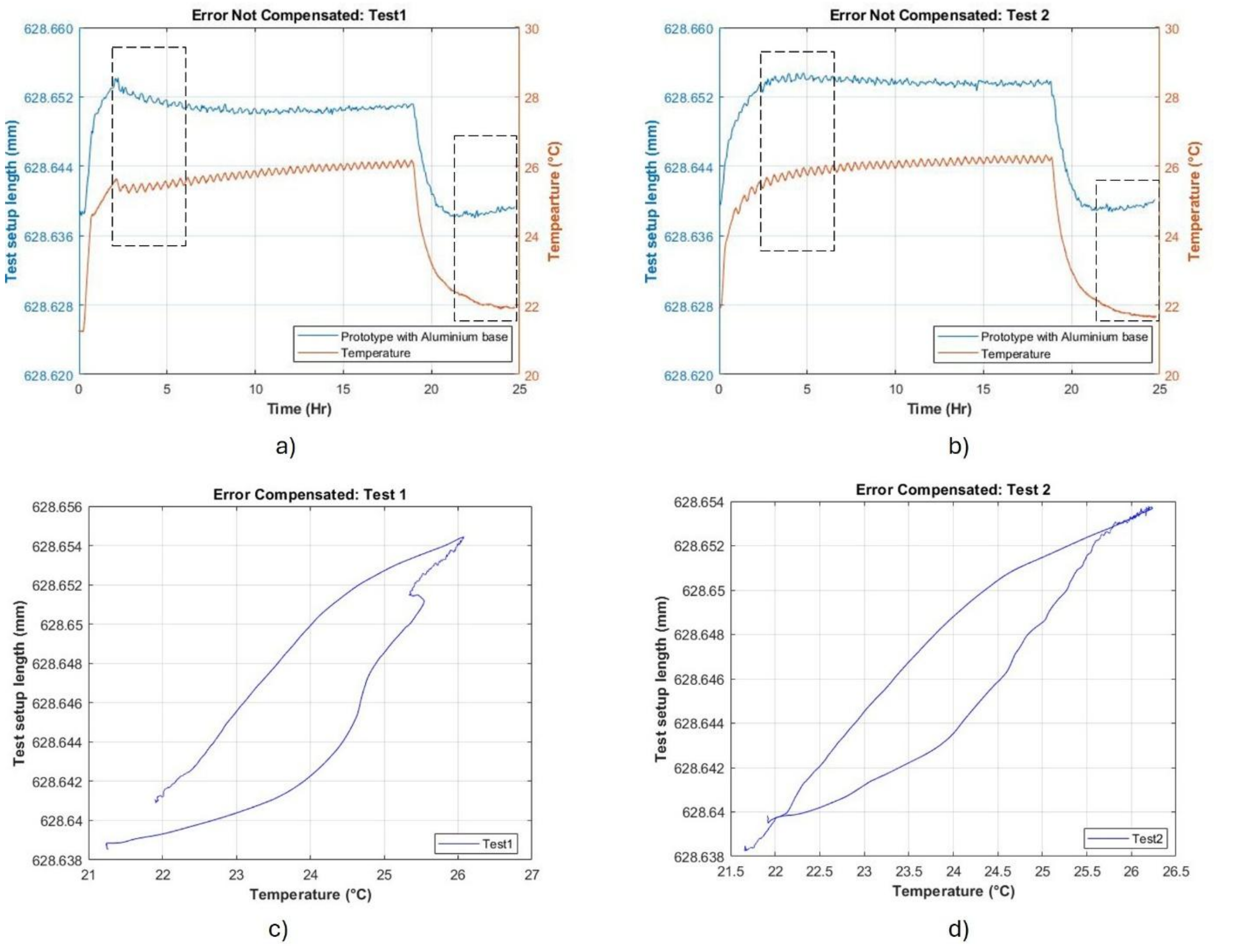


Figure 5. Measured length of test setup up: error not compensated for: a) test 1 b) test 2, Measured length of test setup up: error compensated for: c) test 1 d) test 2

forging method, and its thermal stability was tested using the above detailed approach, as its dimensions exceeded the standard experiment requirements. The prototype was equipped with optic fibre-based sensors, which also restrict localised heating using a closed heating environment, as this can damage the sensor while setting up the experiment or may even alter the properties of the optic fibre. Therefore, a CMM was employed to measure dimensional change with temperature. To compensate for the thermal error in the measurement, a reference was introduced. The change in length of the reference was calculated and deducted from the dimensional measurement of the prototype, and the coefficient of thermal expansion was determined. The CTE of the prototype was calculated to be 3.4 ± 0.1 µm/m.°C. The prototype was found to have a lower CTE compared to the structural components manufactured from cast iron or aluminium alloy, or structural steel, even though it is composed of multiple materials.

The thermal experiment will be carried out on the prototype to check for repeatability and will also be tested for its static and dynamic characteristics. This structural member is anticipated to be used in low to medium-payload robots, which could find applications in high-precision manufacturing.

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Acknowledgement

The authors would like to acknowledge the financial support from UKRI Advanced Machinery & Productivity Initiative (Ref. 84646) and EPSRC Future Metrology Hub (Ref. EP/P006930/1)