High-cycle fatigue of rotating cantilever round copper tube under load-controlled condition

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Abstract. A cantilever rotating bending testing machine accepting only rod specimen with a fixed clamping diameter of 9 mm is modified for tube specimens using two developed adapters. One end of a φ15 mm copper tube is expanded into φ18 mm and forms the tube specimen. Two adapters fitting for φ15 mm and φ18 mm tube ends respectively are designed and fabricated. The φ15 mm adapter is connected to a shaft subject to an applied load and the φ18 mm adapter is connected to a motor, respectively through two collets. Both tube ends are adhered to the inner wall of the adapters with superglue to prevent slippery under the rotation. Finite element analysis is used to estimate the maximum applied stress in the tube specimen i.e. adjacent to the transition for a known counter weight. Only one fatigue test result i.e. at 2.2×10^6 cycles for applied stress of 205 MPa is successfully obtained from the experiment. The collets failed to clamp the adapters for applied stress higher or lower than 205 MPa due to the present of oxide powders resulting from the wear of the collect as it is a 15-year-old machine.

1. Introduction
Copper tubes have been widely used in the plumbing and the Heating Ventilation Air-Conditioning (HVAC) industries due to its excellent heat & electrical conductivity, high corrosion resistant and good formability. These tubes are often bent into small corner radii in the condenser units to have more compact piping design. However, the bent tubes are subject to cyclic bending stress due to the vibration originated from the rotating fan, compressor etc. leading to fatigue failure, particularly at the bent corners [1]. Key components for air conditioners such as evaporator / condenser coils and heat exchangers etc are made of copper. The evaporator tubes directly transfer the heat through a compressor to a condenser unit, and the heat is being removed in this process. In this application, the Copper tubes must hold at certain pressure and be able to perform well at low temperatures. Any failures in the tubes may cause leaking in the cooling system, leading to low cooling efficiency [2]. S-N curve has been used as a criterion for in-house piping stress assessment in the industries. However, this curve is only obtained from rod specimen, but not from the cold drawn copper tube. In the application, the tubes are subject to multi-axial loading. It may not be tension-compression in nature. In the study of copper-phosphorous multi bent tubes in outdoor air-conditioning units, Lim, Mohammad, & Yap reported that the mode shapes of the vibration response of such tubes are not limited to compression-tension. In fact, bending also present hugely in all mode shapes [3]. Martin developed a formula to estimate the endurance limit of the ferrous metal specimen based on the factors such as size, surface finish, loading, temperature, reliability etc [4]. However, it is not applicable for non-ferrous metals such as Copper as it does not have an endurance limit i.e. it will eventually fail for
increase in rotating cycles. Therefore, it is crucial to obtain the fatigue property of the copper tubes particularly at high-fatigue cycle for more accurate in-house piping stress assessment. The study aims to investigate the fatigue property of cold drawn copper phosphorous alloy tube using a modified cantilever rotating bending fatigue test machine for HVAC applications.

2. Material & method
The mechanical and the chemical properties of the tube specimens are shown in Table 1 and Table 2. The minimum tensile strength of 250 MPa is given for annealed tubes. It may increases to 380 MPa due to the cold tube drawing process, resulting into low percentage of total elongation. The copper tube has an outer diameter of 15 mm and wall thickness of 0.7 mm (KEMBLA BS EN 1057 Table X). It is a half-hard temper copper tube with a designation of Cu-DHP or CW024A following European Committee for Standardization (CEN), 2006. It is a commercially-pure copper which has been deoxidized with Phosphorus to leave a relatively high residual content. It is not susceptible to hydrogen embrittlement. The conductivity is relatively low on account of high Phosphorus content.

Table 1. Mechanical Property

| Temper Designation (according to EN 1173) | R250 |
|-------------------------------|------|
| Tensile Strength (min) (MPa)   | 250  |
| Total Elongation (min) (%)     | 30   |
| Hardness (HRB)                | 75 to 100 |
| Maximum Working Pressure (KPa) | 5800 |

Table 2. Chemical Composition (wt %)

|     | Cu | P   |
|-----|----|-----|
|     | > 99.90 | 0.015 to 0.04 |

The schematic and the photo of the cantilever rotating bending fatigue test machine (Hi-Tech Scientific HSM-19 Mark 3) are shown in Figure 1. In the cantilever rotating bending test, non-uniform bending moment is generated along the specimen length with constant load amplitude. The machine has an electronic cycle counter to record the number of rotating cycles during the test. Counter weights are added for obtaining different applied bending stresses in the tube specimens. Originally, it is designed for solid machined specimen with a fixed outer diameter of 9.0 mm at its both ends and a fixed length of 63.7 mm. The solid specimen is mounted onto the machine though a pair of collets. Since the size of the tube specimen in this study is different from the standard solid machined specimen, an adapter is needed to mount the tube specimen to the existing collets. Since it is an old and obsolete machine, collets with other diameters are no longer available in the market, and it is costly and time consuming to fabricate new ones for this study.

The exploded and the assembly drawings for the tube specimen, adapters and collets are shown in Figure 2. One end of the copper tube is expanded from diameter of 15 mm to 18 mm for stress
concentration in the smaller hollow section adjacent to the transition. Two adapters are used to join expanded tube specimen to the existing collets at its both ends. Therefore, it has a 9 mm diameter protrusion in one end to be inserted to the existing collet, and another end to be attached to the specimen in either 15 mm or 18 mm diameter. Both tube ends are adhered to the side wall of the adapters with super glue (Cyanacrylates) to transfer the rotational movement during the test. Since the join are not exerted with tension and compression force but rather a small amount of torque, which is around 1N according to the user manual [5], it can be firmly attached together with the super glue. However, curing time of at least 24 hours is needed to attain the required adhesive strength before performing the fatigue test. After inserting the protrusion of the adapter to the collet, the collet is clamped to prevent slippery under the rotation. To minimize the strain of the glue due to any loading, the adapter is machined to fit into the copper tube end with a tight tolerance. This might remove any movement of the specimen inside the adapter during loading, resulting into the low accuracy of the test.

![Figure 2](image1.png)

**Figure 2. Exploded and assembly views of tube specimen, adapters and collets**

The detailed design of the adaptor for tube end $\phi$15 mm is shown in Figure 3. It has a $\phi$9 mm protrusion with 20 mm length at one end to be inserted to the existing collet. The tube specimen is inserted and glued to the other end of the adapter with an inner diameter of 15 mm and depth of 20 mm.

![Figure 3](image2.png)

**Figure 3. Detailed design of adaptor for tube end $\phi$15 mm**

Shifting of the bracket and the F-clamp of the cantilever rotating bending machine to accommodate for insertion of two adapters is illustrated in Figure 4. Two new holes are drilled in the base plate at approximately 60 mm from original holes away the motor as a new mounting location for the bracket. These modifications are reversible and can be restored to its original structure.

![Figure 4](image3.png)

**Figure 4. Shifting of bracket and F-clamp of cantilever rotating bending machine to accommodate for insertion of two adapters**

Shifting of the bracket and the F-clamp of the cantilever rotating bending machine to accommodate for the extended length between the two collets after the insertion of the two adapters is illustrated in Figure 4. Two new holes are drilled in the base plate at approximately 60 mm from original holes away the motor as a new mounting location for the bracket. These modifications are reversible and can be restored to its original structure.

The detailed designs of tube expander and the photo of the tool are shown in Figure 5. The inner diameter of the tube specimen is expanded from 13.6 mm to 16.7 mm with an expansion ratio of 22.6% using a 10-ton manual hydraulic press. Barreling is observed along the sidewall of the expanded section after piercing the expander into the tube end. An outer die or ring with a clearance of 0.85 mm between the die and the expander is used to flatten the sidewall and to maintain the cylindricity of the expanded section. The cylindricity of the expanded section relative to the original section is measured with a dial gauge. In the measurement, the unexpanded section of the specimen is clamped to a lathe machine and the cylindricity of the expanded section is measured with the dial.
gauge under rotation. A cylindricity value of less than 0.2 mm is obtained in the measurement. Buckling is observed along the unexpanded section for die clearance of less than 0.85 mm.

Finite element analysis is performed using ANSYS to estimate the applied bending stress in the specimen under the controlled load during the fatigue test. In the simulation, the tube specimen is divided with tetrahedral mesh into 37413 elements. The elastic modulus of the tube is 120 GPa. The expanded section is fully constrained. A bending moment of 5880 N.mm is applied at the tube end of the unexpanded section for a counter weight of 40 N. The distance between the applied load and the collet attached to the motor is 147 mm.

3. Results & discussion
The comparison between the location of the fatigue crack in the test and the stress concentration zone in the simulation is shown in Figure 6. The location of the fatigue crack in the test is well predicted in the simulation. The crack is located in the unexpanded section adjacent to the transition. A maximum stress of 204.6 MPa is obtained from the simulation for a counter weight of 40 N.

In the experiment, two types of counter weight blocks are available for the test i.e. 20 N and 2 N. Although it is possible to generate a maximum bending stress of up to 300 MPa in tube specimen with the combination of these weight blocks, the clamp between the collet holder and the collet tend to loose due to the wear of the collet. Oxide powder generated from the collet resulting from the friction and wear for counter weight of 40 N after 2.2 x 10^6 cycles is shown in Figure 7. The clamp failed after thousands of rotating cycles for counter weight of more than 40 N. It also failed after millions of cycles for counter weight lower than 40 N. Therefore, only one set of data could be obtained with the existing setup. Since the collet has been used for more than 15 years in the test, the clamping force exerted onto the protrusion is getting weaker resulting from the wear. It is also difficult to fabricate new collets due to the lack of accurate and detailed dimensions of the worn part. There is also no spare part available in the market as the machine is obsolete. However, Stephens et al. reported that S-N curves from torsional or bending load-control test tend to have no data at lower fatigue life, i.e.: $10^3$ or $10^4$ cycles due to the significant plastic deformation [6].
The comparison of fatigue strength among different test methods for pure copper is shown in Table 3. Zainuddin et al. reported that the fatigue strength of 320 MPa in a 3-point bending fatigue test of copper tube at $2.2 \times 10^6$ cycles [7]. Farshbaf & Habibi reported the fatigue life of more than 10 million cycles for bending stress of 200 MPa in rotating bending fatigue test of solid machined specimen. At around 2.2 million cycles, the bending stress is around 225 MPa [8].

| Test method                     | Specimen          | Fatigue strength @ $2.2 \times 10^6$ cycles (MPa) |
|---------------------------------|-------------------|-----------------------------------------------|
| 3-point bending [7]             | Round tube        | 320                                           |
| R-R Moore rotating bending [8]  | Solid specimen    | 225                                           |
| This study                      | Round tube        | 205                                           |

4. Conclusion
In this study, the conventional cantilever rotating bending fatigue test machine accepting only rod specimen with a fixed clamping diameter of 9 mm is modified and the fatigue life of an expanded copper tube specimen with a diameter of 15 mm is successfully obtained. The diameter of one tube end is expanded from 15 mm to 18 mm and straightened for stress concentration adjacent to the transition in the smaller section. Two adapters are designed and fabricated in this modification for mounting the expanded tube specimen to the machine through the collets. The fatigue strength of the tube specimen at $2.2 \times 10^6$ cycles is 205 MPa using a counter weight of 40 N. The strength is lower than the other reported results for the same material at $2.2 \times 10^6$ cycles. Due to loose of the clamp resulting from the wear of the collet, only the fatigue test for bending stress of 205 MPa is successfully completed. The clamp tends to loose for counter weight of more than 40 N or for fatigue life of more than millions of cycles using counter weight of less than 40 N.

5. Reference
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