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TECHNICAL ARTICLE

Determining the Stress Distribution in a Bicycle Crank Under In-Service Loads

J.A. Calvo Ramos, C. Álvarez-Caldas, A. Quesada, and J.L. San Román

Departamento de Ingeniería Mecánica, Universidad Carlos III de Madrid, Madrid, Spain

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Correspondence
J. A. Calvo Ramos,
Departamento de Ingeniería Mecánica,
Universidad Carlos III de Madrid,
Avenida de la Universidad,
30, Leganés 28911 (Madrid),
Spain
Email: jacalvo@ing.uc3m.es

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Abstract

New techniques have been introduced in the design process of most of the components of a bicycle. One of the main purposes of this introduction is trying to achieve the best weight/rigidity relation. However, all these advances have to take into account the security of the rider. Unexpected failures of some components such as stem, handlebar, or cranks, can cause serious injuries to cyclists and have to be prevented. Standard EN 14781:2006 establishes the safety and performance requirements that every bicycle and every component must fit from the point of view of fatigue failure. In this work, several bicycles cranks will be experimentally tested under the loading conditions of the reference standard. The stresses on the critical points will be analyzed to determine the influence of any variation in the test conditions. According to obtained data, several changes in the conditions of the standard will be proposed. Also, loading tolerance values for the test will be suggested, because they are not established in the standard.

Introduction

Cycling sector has experienced huge technological advances in the past 2 decades. Customers demand minimum weight and maximum rigidity. Therefore, manufacturers have to use increasingly sophisticated materials and designs. New techniques have been introduced in the design process of most of the components of a bicycle, trying to achieve the best weight/rigidity relation. Materials such as carbon fibre or high-strength aluminium, as well as the use of finite element analysis (FEA), are widely extended.

However, all these advances have to take into account the security of the rider. Unexpected failures of some components such as stem, handlebar, or cranks, can cause serious injuries to cyclists and have to be prevented. To ensure that these components meet minimum strength and durability requirements, European Committee for Standardization (CEN) published standard EN 14781:2006.[1] This standard establishes the safety and performance requirements that every bicycles and every components must fit from the point of view of fatigue failure.

On the other hand, the US standard was promulgated by the US Consumer Product Safety Commission under authority of the Hazardous Substances Act. In an effort to reduce bicycle and component failures and to standardize bicycle manufacturers' testing procedures, a new standards development activity was undertaken by ASTM Committee F08 on Sports Equipment and Facilities when it formed Subcommittee F08.10 on bicycles. The standards have been developed to test bicycle forks, test non-powered bicycle trailers, and test methods for bicycle frames. Other areas of technical interest, such as bicycle wheels, used the international standards from European representative as EN 14781:2006.

In order to guarantee a minimum of security, in most markets (USA, EU, etc. it is essential to demonstrate compliance with these requirements or similar to be able to distribute both bicycles and their components. In this work, several bicycles cranks will be experimentally tested under the loading conditions of the reference standard. The stresses on the critical points will be analyzed to determine the influence of any variation in the test conditions.

According to obtained data, several changes in the conditions of the standard will be proposed. Also, loading tolerance values for the test will be suggested, because they are not established in the standard.

In-Service Loads in the Cranks

The stress distribution in the bicycle crank is very complex. When the load is applied in the pedal, combined flexion and torsion loads appear in the crank. These loads act in two different planes, producing the deformation shown in Fig. 1 (The results shown in Fig. 1, come from a finite elements simulation model performed by the authors.)

The load distribution changes when the crank moves from the upper point of its working cycle (+90°) to the lower one (−90°). The proportion between torsion and flexion varies, producing very complex variations in the stress distribution. So, when trying to evaluate the fatigue strength of the component, it is necessary to find the position where the worst stress distribution is produced. In this way, the crank will be tested in the position that produces maximum stresses in the critical points. On the other hand, it is necessary to take into account the biomechanics of pedalling, because the cyclist is not able to apply the same load on the pedal all along the working cycle of the crank.

In 1993, Kautz and Hull[2] determined on a sample of professional cyclists the distribution of the load along the pedalling cycle. This distribution is shown in Fig. 2. As can be seen, the maximum load on the pedal appears in the area between +30° and −45°. The maximum load peak depends on the personal technique used by the cyclist, although it is possible to assume that it is contained between −10° and −15°.[3,4]

The magnitude of the load is different depending on the position of the cyclist. Soden and Adeyefa[5] demonstrated that, when seated on the seat, at a rhythm of 90 rpm and a stem of 434 W, the effective load is 0.8 times the weight of the cyclist. The more the stem increases, the more the load approximates to the real weight of the cyclist. If the cyclist is standing on the pedals, ascending a slope, the force can reach 2.5 times the weight of the rider.

According to these data, the stress distribution is being analyzed in the following points: 0, +30, +45, +60, −30, −45, −60° of the working cycle of the crank (shown in Fig. 2). The angle was measured with a digital goniometer with an accuracy of 0.1°.

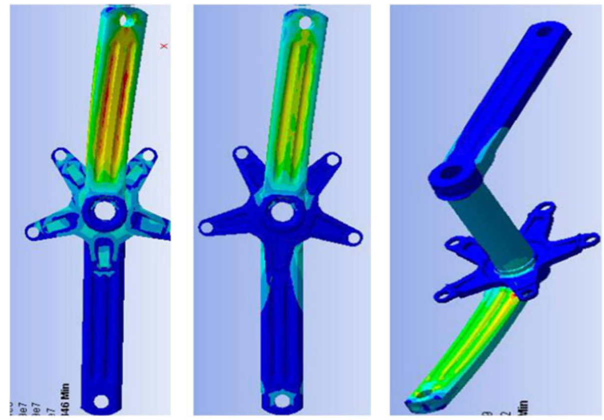

Figure 1 Deformed shape of the crank under in-service loads.

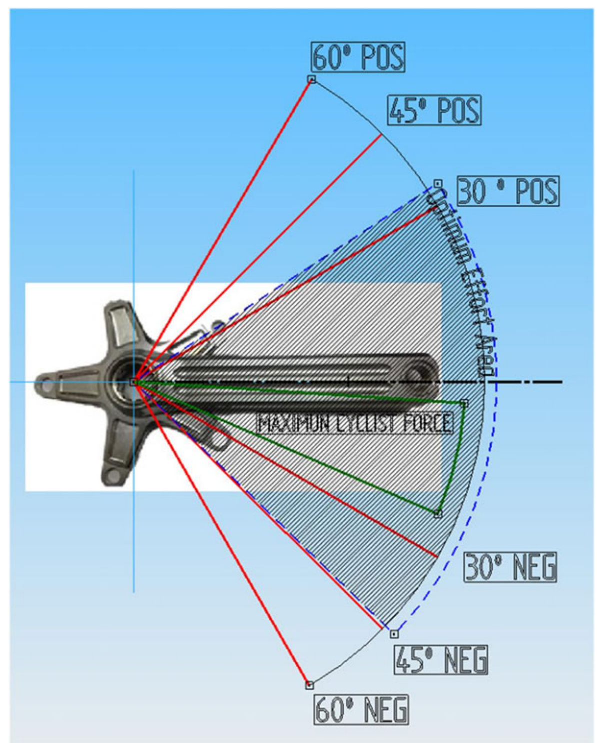

Figure 2 Distribution of the load along the pedaling cycle.

Fatigue-Strength Test

According to the chapter 4.12.7 of the standard, bicycle cranks have to overcome a fatigue-strength test. In such a test, the assembly (including the chain ring and the bottom bracket with its bearings) has to be fixed to an implement that represents the bicycle frame. The angle between the crank and the horizontal plane has to be 45°, and the assembly has to be blocked with the chain so that the crank cannot turn. Afterwards, a

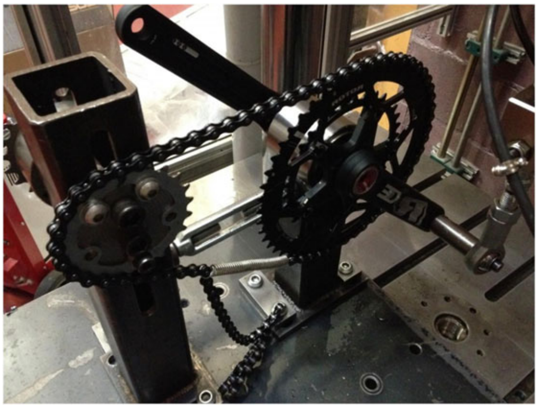

Figure 3 Cranks placed forming 45° with the horizontal.

vertical sinusoidal load is applied in a point placed on the pedal axle at a distance of 65 mm from the crank. The load varies from 0 to 1800 N with a maximum frequency of 25 Hz. Figure 3 shows the test assembly:

The crank is considered suitable if it overcomes 100,000 load cycles and no defect appears during the test.

The standard does not established tolerance values for the load or for the position of the crank, so the results of the tests can vary from one lab to another according to the criteria applied for these two things.

Stress Measurement

Under previous test conditions, stresses have been measured by strain gauges placed in localized points of the crank. These sensors are rectangular rosettes with a length of 2 mm. The reference of the gauges used is FRA-2-23-1L (Tokyo Sokki Kenkyujo Co., Ltd., Tokyo, Japan).

The gauges were placed in those critical points where cracks use to appear according to previous fatigue tests. Figure 4 shows some examples of the appearance of cracks during fatigue tests. These tests were carried out in a hundred of cranks with different geometries and materials by the authors in order to validate both the design and the manufacturing process for a family of components. The results of the fatigue test are very similar in most cases, so it was decided to make stress measurements only on the most representative model.

On account of this, the strain gauges have been placed in three measurement points. Figure 5 shows these positions. Taking into account the kind of rosette gauge as well as its gauge distribution shown in Fig. 6, main strains and main stresses can be obtained through the following expressions.

Equations 1 and 2 allow to obtain the maximum and the minimum strain in the rosette:

$$\varepsilon_{\max} = \frac{1}{2}\cdot\left[\varepsilon_1+\varepsilon_2+\sqrt{2\cdot\left|(\varepsilon_1-\varepsilon_3)^2+(\varepsilon_2-\varepsilon_3)^2\right|}\right] \quad (1)$$

$$\varepsilon_{\min} = \frac{1}{2}\cdot\left[\varepsilon_1+\varepsilon_2-\sqrt{2\cdot\left|(\varepsilon_1-\varepsilon_3)^2+(\varepsilon_2-\varepsilon_3)^2\right|}\right] \quad (2)$$

The maximum shear strain and the direction for the principal axes relative to the reference grid can be calculated with Eqs. 3 and 4:

$$\gamma_{\max} = \sqrt{2\cdot\left|(\varepsilon_1-\varepsilon_3)^2+(\varepsilon_2-\varepsilon_3)^2\right|} \quad (3)$$

$$\theta_{\max} = \frac{1}{2}\cdot\tan^{-1}\cdot\left|\frac{2\cdot\varepsilon_3-(\varepsilon_1+\varepsilon_2)}{\varepsilon_1-\varepsilon_2}\right| \quad (4)$$

In the same way, maximum and minimum stresses can be obtained through expressions 5 and 6:

$$\sigma_{\max} = \frac{E}{2}\cdot\left(\frac{\varepsilon_1+\varepsilon_2}{1-\nu}+\frac{1}{1+\nu}\cdot\sqrt{2\cdot\left|(\varepsilon_1-\varepsilon_3)^2+(\varepsilon_2-\varepsilon_3)^2\right|}\right) \quad (5)$$

$$\sigma_{\min} = \frac{E}{2}\cdot\left(\frac{\varepsilon_1+\varepsilon_2}{1-\nu}-\frac{1}{1+\nu}\cdot\sqrt{2\cdot\left|(\varepsilon_1-\varepsilon_3)^2+(\varepsilon_2-\varepsilon_3)^2\right|}\right) \quad (6)$$

Equation 7 is the expression for the maximum shear stress:

$$\tau_{\max} = \frac{E}{2\cdot(1+\nu)}\cdot\sqrt{2\cdot\left|(\varepsilon_1-\varepsilon_3)^2+(\varepsilon_2-\varepsilon_3)^2\right|} \quad (7)$$

Finally, Von Mises stress can be obtained as shown in Eq. 8:

$$\sigma_{VM} = \sqrt{\sigma_{\max}^2+\sigma_{\min}^2-(\sigma_{\max}\times\sigma_{\min})} \quad (8)$$

Each strain gauge has been set up by a Wheatstone quarter bridge, and all of them are connected to a NEC SAN-EI AS2101 amplifier. Signals have been acquired and stored with an IMC CRONOS data acquisition equipment connected to a PC. The load is applied by a hydraulic cylinder that has a load cell and a displacement sensor to control the test. The data acquisition system also registers the load applied by the cylinder on the pedal axle and the displacement of this cylinder.

Material Properties

Aluminium 7075-T6 is the most used material in the construction of cycle cranks. Its mechanical properties can be seen in Table 1.

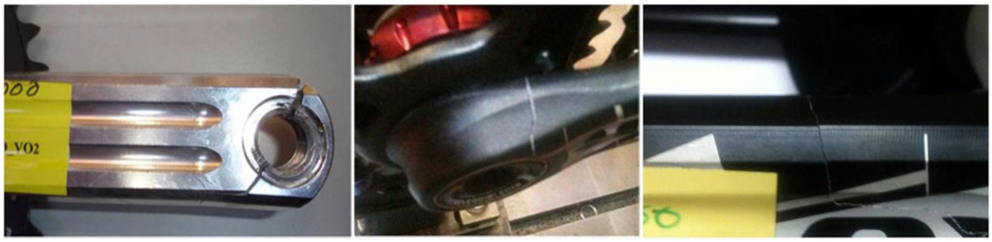

Figure 4 Appearance of cracks during fatigue tests.

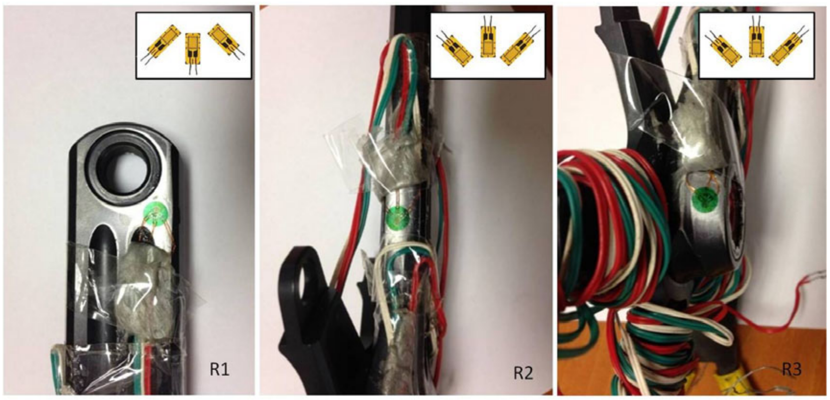

Figure 5 Positions of the strain gauges R1 (left), R2 (middle), and R3 (right).

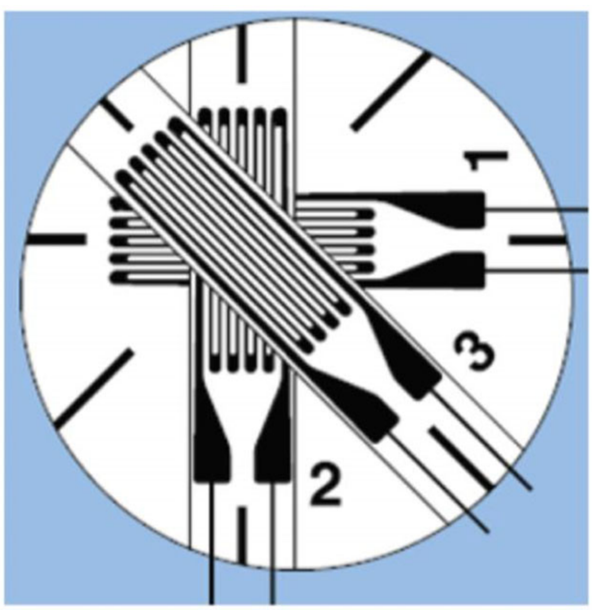

Figure 6 Gauge distribution.

Table 1 Aluminium 7075-T6 properties

Properties	Value	Unit
Density	2810	Kg/m^3
Tensile strength	470–528	MPa
Yield strength	420–450	Mpa
Elongation at break	10	%
Young's modulus	72	GPa
Poisson's ratio	0.33	

Results

The relationship between the stresses measured by each rosette and the load applied in the pedal has been analyzed for different positions of the working cycle of the crank. By doing this, it is possible to find the most critical position and also to determine the sensitivity of the test when some of the standard conditions change.

Figure 7 shows maximum stress results for each rosette (vertical axle) against vertical load (horizontal axle). One path has been drawn for each position of the crank. As expected, there is a linear relationship between the applied load and the registered stress.

For rosette 1 (R1), positions over the horizontal register the maximum compression stresses. Over $+30^\circ$, compression turns into traction. Its maximum is achieved at -60°, although there are no big differences among -30°, -45°, and -60°. This implies that varying the test position within this range does not significantly affect stresses in rosette 1 area.

For rosette 2 (R2), all the positions cause traction stresses. The maximum is achieved at the horizontal

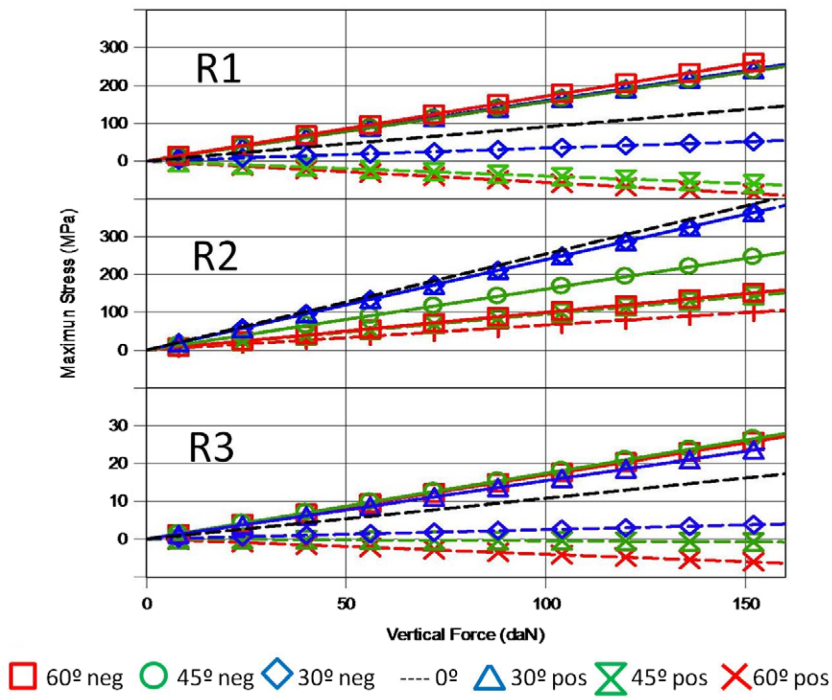

Figure 7 Maximum stress versus vertical load for different positions of the crank.

position. The value registered at -30° position is very similar to the maximum. For all the other positions, stress values decrease noticeably.

For rosette 3 (R3), maximum stress values are 10 times smaller than rosette 1 and 2 values. There is also a change between compression (positive positions) and traction (negative positions). The maximum is achieved at -60°, as in rosette 1. Values for positions -30 and -45 are very similar to this maximum.

As explained before, rosette 3 is the less sensible. Figure 8 shows the variation of the slope of the relationship Stress/vertical load when the position of the crank changes. As can be shown, slope is mostly constant for crank positions between -30° and 30°. This happens for every kind of stress: maximum, minimum, and Von Mises. This effect can be seen in every rosette. Slopes in the pedal area (R1) and in the crank arm (R2) are similar, although the slope in the pedal area is slightly greater that the crank arm's one. In the tested points, the direction of the maximum stress is normal to the direction of the fissures appeared in real specimens. Is has been also observed that maximum stress values are very close to the maximum values of the material.

Conclusions

According with previous expositions and results, it can be concluded:

- If the magnitude of the load indicated in the standard is applied to the crank, the obtained Von Mises stresses are under the material limits. In fact, the maximum Von Mises stress is registered by rosette R2 and has a value of 396 MPa. It appears when a working vertical load is applied according to the standard specification. The minimum yield strength of the material is 420 MPa.
- Measured stresses are always proportional to the applied vertical load, independently of the rosette.
- The highest stresses for every point of the crank appear for the position of -30°. This position corresponds also with the area in which the load applied by the cyclist is the maximum.
- In this position, the sensitivity of the test for angle variations is very low. Because of this, if there was any error placing the crank in the test device, it will not produce important variations in the results.
- The most stressed area is the crank arm (rosette 3).

Taking into account these conclusions, the authors propose a modification on the standard[1] so that the position of the crank during the test is -30° instead of the present -45°. This will reduce the influence of the exactitude of the position on the results. The stresses on the component will also be higher and the test will reproduce better the real working conditions of the crank when a cycling is ridding the bike.

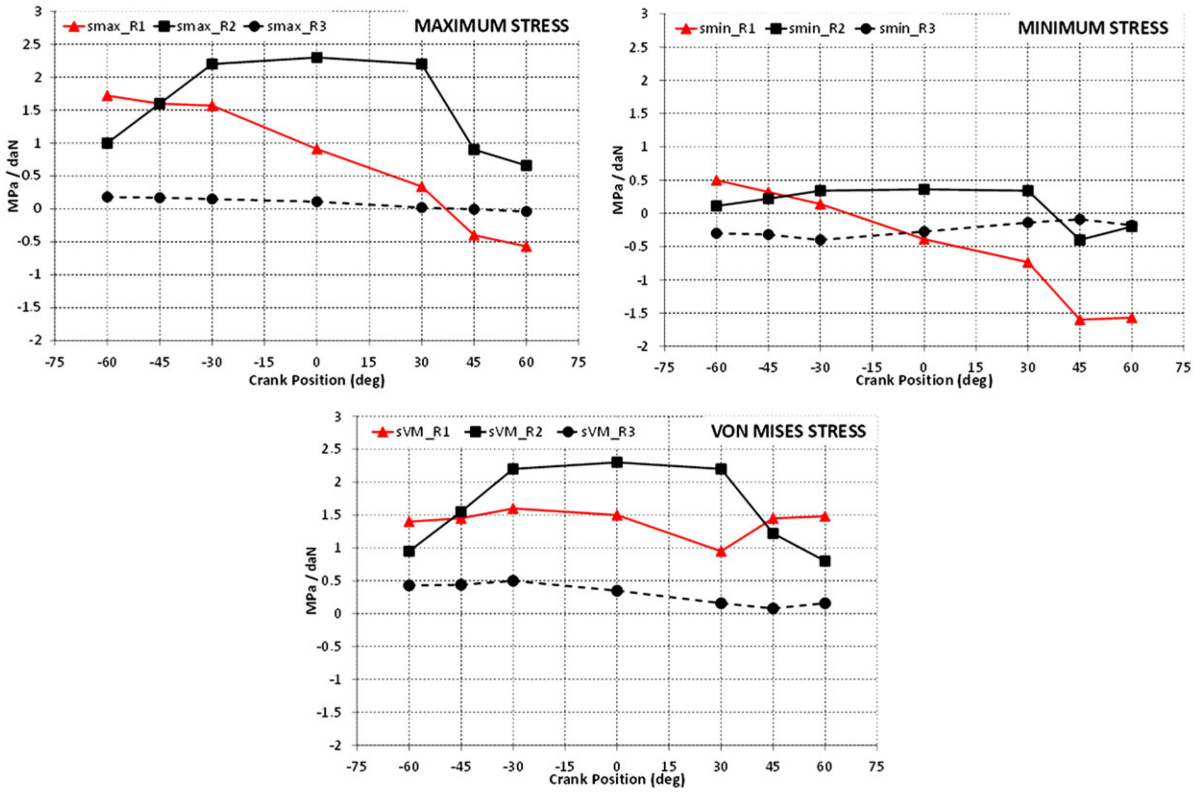

Figure 8 Variation of the slope of the relationship stress/vertical load when the position of the crank changes.

Authors also recommend a tolerance for the load applied in the test. As the measured Von Mises stress is a 10% smaller than the yield strength of the material, this tolerance must be between 0 and +5% of the nominal value. Because it is so close to the maximum strength of the material, the suggested tolerance of the load is in the limit admissible.

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