A single loading direction for fatigue life prediction and testing of handlebars for off-road bicycles

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Abstract

Components for off-road bicycles including handlebars continue to be recalled with regularity because of problems with structural failure as a result of high cycle fatigue in the off-road environment. The objectives of this study were to 1) devise a method for determining the point on the handlebar cross section that experiences the maximum cumulative damage when the handlebar is subjected to loads applied by the rider’s hands that vary randomly in both magnitude and direction, 2) use this method with an existing database of handlebar loads (DeLorenzo and Hull, J Biomech Eng, 1999) to determine a single loading direction to be used in design and testing of the handlebar, and 3) determine the sensitivity of the point of maximum cumulative damage to structural and material properties of the handlebar. The load database was generated by seven subjects who rode a rough downhill course in the standing posture and provided a total of 28 trials for analysis. For each of the 28 trials, the stress histories at 1-degree increments around the handlebar circumference were determined. The cumulative damage at each of the 360 points for each of the 28 trials was computed using rainflow counting in conjunction with Walker’s equation to represent the S-N diagram for the handlebar material. The maximum cumulative damage varied by more than six orders of magnitude between trials and the location of the point of maximum damage ranged from $110^\circ$ to $343^\circ$ (angle measured from horizontal axis pointing forward with positive counterclockwise rotation viewed from the right side of the bicycle). The median location was $142^\circ$. To create a tensile stress in bending at $142^\circ$, a load would have to be applied at $322^\circ$ ($322^\circ = 142^\circ + 180^\circ$). Thus, $322^\circ$ was found to be the single loading direction representative of the variable-direction load database. This direction did not change for a handlebar with different structural and material properties and coincided approximately with a vector drawn along the line of the arms of the rider. This loading direction can be used in conjunction with information on the effects of assembly of the handlebar with a stem to analytically predict the high cycle fatigue life of a particular stem/handlebar assembly. Furthermore, this loading direction can also be used to experimentally determine the expected in-service fatigue life of a particular stem/handlebar assembly. © 2002 Elsevier Science Ltd. All rights reserved.

1. Introduction

Many different bicycle components including handlebars have been recalled because they break during use [1,2]. These recalls are costly for manufacturers and dangerous to riders. To prevent structural failure of the components in the off-road environment, which could lead to serious injury, this study was intended to assist in the design and product qualification of the handlebar.

To provide this assistance, one quantity that is important to determine is the direction of loading that produces the most fatigue damage in the handlebar independent of the effects of assembly of the handlebar with the stem. Hereafter this quantity is called the direction of maximum damage. This direction is important to determine because the prediction of fatigue life and fatigue testing of the handlebar are complicated by the variable-direction and variable-amplitude loading that the handlebar experiences in the field. If the direction of maximum damage were known, then it could be used in single-loading axis predictions of high cycle fatigue life for a particular stem/handlebar assembly and also in fatigue testing for product qualification.

Determining the direction of maximum damage requires a methodology that accounts for the nature of the loading developed by the hands on the handlebar during off-road cycling. Loads applied by the hands to
the handlebar can be conceived as being one of three types. One type is rider-induced loads which occur as a result of muscular actions of the rider during pedaling. A second type is terrain-induced loads which occur as a result of inertial loads of the rider caused by the bicycle traveling over surface irregularities. A third type is control-induced loads which occur as a result of control actions on the part of the rider such as braking and steering. Inasmuch as terrain-induced loads are generally superimposed on rider-induced and/or control-induced loads, the loading picture is random with variations in both magnitude and direction. Accordingly, to determine the direction of maximum damage, a methodology must be devised which determines the point on the handlebar circumference that experiences the maximum cumulative damage caused by field loading. A previous study determined a single direction of loading based on a correlation analysis of the load components in the plane of the bicycle but did not consider the damage created by the applied loads [3]. Therefore the first objective of this study was to devise a method for determining the single direction of loading which causes the maximum damage.

A database of field loading on the handlebar exists for determining the direction of maximum damage. In a previous study [4], loading data were collected from an instrumented handlebar while seven subjects coasted at relatively high speed (approximately 8.9 m/s = 20 mph) over a rough downhill course. The instrumented handlebar measured the two force components applied by each of the hands in the plane of the bicycle. Considering that no previous study known to the authors has determined the direction of maximum damage, the second objective of the present study was to determine the direction of maximum damage for the database provided by De Lorenzo and Hull [4] using the method devised to satisfy the first objective above.

Methods that determine cumulative damage consider the stresses imposed by the applied loads, often in conjunction with the stress-life behavior of the material. Accordingly both the structural and material properties of the handlebar have the potential to affect the point on the handlebar circumference that experiences maximum cumulative damage. Therefore, the final objective was to assess the effect of different structural and material properties on the point that experiences the maximum damage.

2. Methods

One handlebar modeled in this study was typical of the current models commonly available in the retail market. The handlebar was a commercially available mountain bike handlebar, 580 mm long with a 6-degree bend. The handlebar was made from 6061-T6 aluminum. The material properties of this alloy are summarized in Table 1 and the smooth specimen fatigue data for 6061-T6 aluminum are plotted in Fig. 1 for various stress ratios. The curves in Fig. 1 are the result of the Walker equation and fit the data well over a wide range of stress ratios. The conditions of the downhill ride from which the database was obtained were typical of common conditions of mountain biking. The seven subjects were experienced recreational riders who weighed on average 75.6 kg and were 180 cm tall (Table 2). The terrain for the trials consisted of a straight trail with an 8% downhill grade containing rocks, ruts and washouts. The bicycle used was a full suspension design (1995 FSR, Specialized Bicycle Components, Morgan Hill, CA) that had the ability to disable the rear suspension. The reference frame for the handlebar loads placed the positive X-axis pointing forwards (parallel to ground), the positive Z-axis pointing upwards (normal to ground), and the angle $\theta_0$ was the angle relative to the X-axis with positive counterclockwise when viewed from the right side of the bicycle (Fig. 2). During a 30-s ride, force components in both the X and Z-directions were recorded every 5 ms on both sides of the handlebar. Each of the seven subjects rode twice in the standing position with the rear suspension active in one ride and inactive in the other ride. Because the loads applied by the hands to each side of the handlebar were recorded, a total of 28 (7 riders×2 sides of the handlebar) different 30-s trials were available from this database.

To characterize both the consistency and variability in the downhill ride data, several quantities were computed for each trial and across all trials. For each trial, the root mean square (RMS) of the magnitude of the resultant force vector over the duration of a trial was computed to indicate the general magnitude of the loading. Across all trials, histograms of the magnitude and direction of the resultant force vector were also computed to indicate the distributions of these quantities. In constructing these histograms, the interval sizes for the magnitude and the direction of the force vector were 10 N and 10° respectively.

To compute the direction of maximum damage, several calculations similar to a variable amplitude load

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**Table 1**

Handlebar geometry and material properties for 6061-T6 aluminum [6]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside diameter</td>
<td>25.40 mm</td>
</tr>
<tr>
<td>Wall thickness</td>
<td>2.19 mm</td>
</tr>
<tr>
<td>Modulus of elasticity</td>
<td>73.1 GPa</td>
</tr>
<tr>
<td>Ultimate strength</td>
<td>310 MPa</td>
</tr>
<tr>
<td>Yield strength</td>
<td>276 MPa</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.345</td>
</tr>
<tr>
<td>Walker equation exponent</td>
<td>0.63</td>
</tr>
<tr>
<td>Fatigue life equation denominator</td>
<td>871.5 MPa</td>
</tr>
<tr>
<td>Fatigue life equation exponent</td>
<td>−9.84</td>
</tr>
</tbody>
</table>
Fig. 1. Plot of maximum stress versus fatigue life for 6061-T6 aluminum [6]. The curves are computed from the Walker equation.

Table 2
Rider’s height, weight, mean speed, and maximum speed for the downhill ride database

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Height</th>
<th>Weight</th>
<th>Speed mean</th>
<th>Speed max</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m</td>
<td>kg</td>
<td>m/s</td>
<td>m/s</td>
</tr>
<tr>
<td>Maximum</td>
<td>1.85</td>
<td>79</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>Minimum</td>
<td>1.73</td>
<td>68</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>Mean</td>
<td>1.80</td>
<td>75.6</td>
<td>8.5</td>
<td>11.1</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.038</td>
<td>3.5</td>
<td>1.1</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Fig. 2. Diagram illustrating the reference frame used for the handlebar.

Fatigue life prediction were made. First, the stresses developed in the handlebar as a result of forces from the riders’ hands were determined. These forces were considered as inputs to a cantilever beam with the fixed end of the beam being the handlebar stem clamp. From basic beam theory, neglecting the small torsion due to the 6° bend and possible biaxial effects, the maximum stress generated from cantilever loading is:

\[
\sigma = \frac{l r_o}{I} F
\]  

where \(l\) is the length of the cantilever measured from the center of the rider’s hands to the edge of the handlebar clamp, \(r_o\) is the outer radius of the handlebar, \(I\) is the moment of inertia, and \(F\) is the applied load. Because the loading measured during the downhill riding was in two directions along the \(X\)- and \(Z\)-axes, the stress around the outer surface of the handlebar was calculated from:

\[
\sigma(t, \theta_b) = \frac{l r_o}{I} (F_x(t) \sin(\theta_b) + F_z(t) \cos(\theta_b))
\]  

where \(F_x(t)\) and \(F_z(t)\) are force components as a function of time \(t\) from the loading database along the \(X\) and \(Z\)-axes respectively. For the handlebar analyzed, the geometric parameters at the cross-section of interest had the following values: \(l = 250\) mm, \(r_o = 12.7\) mm, and \(I = 10,849\) mm\(^4\). \(\theta_b\) ranged from \(0^\circ\) to \(360^\circ\) in \(1^\circ\) increments.

At a given point on the handlebar, the stresses calculated from eq. (2) were input to a cycle counting and cumulative damage computation. The stresses from each of the 28 trials were analyzed to determine the stress cycles in the data using rainflow counting [5]. The rainflow counting method produced a set of stress amplitudes and their corresponding mean stresses from the ride data. Next, for each pair of stress amplitude, \(\sigma_a\), and corresponding mean stress, \(\sigma_m\), the Walker equation was used to determine an equivalent zero-to-tension stress, \(\sigma_{eq}\), using:
\[ R = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}} = \frac{\sigma_u - \sigma_m}{\sigma_u + \sigma_m} \]  
(3)

\[ \sigma_{eq} = \sigma_{\text{max}} (1 - R)^{0.63} \]  
(4)

where \( R \) is the stress ratio and \( \sigma_{\text{min}} \) and \( \sigma_{\text{max}} \) are the maximum and minimum stresses for a given cycle. The Walker equation exponent 0.63 in eq. (4) was taken from Military Handbook 5G [6]. For each value of the equivalent stress, the corresponding fatigue life for constant amplitude loading was determined from:

\[ N_f = \left( \frac{\sigma_{eq}}{871.5} \right)^{-9.84} \]  
(5)

where the fatigue life equation constants (i.e., \(-9.84, 871.5\)) were converted to metric units from values given in Military Handbook 5G [6], and \( N_f \) is the number of cycles to failure for \( \sigma_{eq} \), which is given in MPa. Using Miner’s rule [7,8], the damage \( d \) was calculated for each pair of stress amplitude and mean stress using:

\[ d = \frac{1}{N_f} \]  
(6)

where \( d \) is the damage associated with a given \( N_f \).

For a particular downhill trial, the cumulative damage \( D \) was the sum of all the damages \( d \) for the set of stress amplitude and mean stress pairs found by rainflow counting the stress history at a specified location. The point of maximum damage for each trial was the location of the largest damage found among all 360 points around the bar. The direction of maximum damage was the direction along which a load would have to be applied to have the maximum bending stress occur at the point of maximum damage. Therefore, the direction of maximum damage can be represented by a vector pointing from the point of maximum damage to the center of the handlebar axis. To illustrate the nature of damage in the handlebar, the damage was plotted as a function of angle \( \theta_x \) around the handlebar for both the most and least damaging trials.

To assess the influence of different material and structural properties of the handlebar, the point of maximum cumulative damage also was computed for a commercially available handlebar made from 2024-T4 aluminum. From Table 4, which indicates the geometry, material properties, and Walker coefficients of this alternative handlebar, note that the wall thickness is less for the 2024-T4 handlebar than for the 6061-T6 handlebar (Table 1). Further the quantities used in eqs. (4) and (5) to assess the cumulative damage are different between the two handlebars.

### 3. Results

The handlebar ride database was composed primarily of resultant forces with small magnitudes. The root mean square (RMS) resultant force magnitude for the 28 trials ranged between 60 and 110 N (Fig. 3). The resultant force magnitude that occurred most often was 45 N (Fig. 4) and the resultant force angle that occurred most often was 305° (Fig. 5).

For a particular trial, the damage varied around the 6061-T6 handlebar (Fig. 6). Although the RMS resultant force magnitudes were similar, the maximum cumulative damage generated from each trial varied by six orders of magnitude. Trial 8 produced the most damage, trial 24 produced the least damage, and trial 26 produced the median for all trials. Despite the differences in the amount of damage, the patterns for the distribution of damage around the circumference of the handlebar were comparable for these trials. The regions with very small damage were those regions near the neutral axis of bending (i.e., ± 90° from the locations with the largest damage).

The point of maximum damage in the 6061-T6 handlebar varied from trial to trial. Because the median of these angles was 142° and the mean and mode were comparable to the median (Fig. 7, Table 3), the median was used to define the overall point of maximum damage. To create a tensile stress in bending at an angle of 142°, a load would have to be applied at 322° (322° = 142°+180°). Thus, 322° was found to be the direction of maximum damage.

### Table 3
Statistics for the maximum damage and direction of maximum damage in the 6061-T6 handlebar for all trials in the downhill ride database

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Damage ( D )</th>
<th>Angle, degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>9.53E-06</td>
<td>166.8</td>
</tr>
<tr>
<td>Median</td>
<td>1.60E-07</td>
<td>142</td>
</tr>
<tr>
<td>Mode</td>
<td>#N/A</td>
<td>141</td>
</tr>
<tr>
<td>Maximum</td>
<td>1.41E-04</td>
<td>343</td>
</tr>
<tr>
<td>Minimum</td>
<td>9.10E-10</td>
<td>110</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>3.08E-05</td>
<td>65.0</td>
</tr>
</tbody>
</table>

### Table 4
Handlebar geometry and material properties for 2024-T4 aluminum [6]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside diameter</td>
<td>25.40 mm</td>
</tr>
<tr>
<td>Wall thickness</td>
<td>1.78 mm</td>
</tr>
<tr>
<td>Modulus of elasticity</td>
<td>73.1 GPa</td>
</tr>
<tr>
<td>Ultimate strength</td>
<td>460 MPa</td>
</tr>
<tr>
<td>Yield strength</td>
<td>380 MPa</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.345</td>
</tr>
<tr>
<td>Walker equation exponent</td>
<td>0.52</td>
</tr>
<tr>
<td>Fatigue life equation denominator</td>
<td>1349 MPa</td>
</tr>
<tr>
<td>Fatigue life equation exponent</td>
<td>-9.09</td>
</tr>
</tbody>
</table>
When the point of maximum damage was determined for the 2024-T4 handlebar using the same methods as those used for the 6061-T6 handlebar, the median angle was found to be 141°. Thus the 2024-T4 handlebar had an angle of maximum damage which differed by only 1° from that of the 6061-T6 handlebar.

4. Discussion

Towards designing and qualifying handlebars so that they are not prone to failure as a result of high cycle fatigue in the off-road environment, the objectives of the work reported by this paper were to: 1) devise a method to determine the point of maximum cumulative damage around the handlebar circumference, 2) determine the direction of maximum damage using an existing database of handlebar loads, and 3) investigate the sensitivity of the point of maximum damage to structural and material properties of the handlebar. The key findings were that: 1) the point of maximum damage was determined using Miner’s rule and rainflow counting in conjunction with the Walker equation to represent the S-N diagram of the handlebar material, 2) the direction of
maximum damage was 322° due to downhill riding, and 3) the point of maximum damage varied by only 1° for the two handlebars analyzed. Before discussing the importance of these findings, several methodological aspects of the study should be reviewed critically because of their potential to influence the findings.

4.1. Methodological issues

To determine a meaningful direction of maximum damage, it was important to use realistic loading that reflected all of the important factors that could influence this direction in off-road cycling, one of which is the riding condition. The use of a database for downhill riding restricts the applicability of the direction of maximum damage to only one of the many riding conditions. This is not a major limitation however. While different riding conditions (e.g. gradual uphill climbing) would produce different loads and presumably different directions of maximum damage, the magnitudes of loading and the corresponding damage to the handlebar in those riding conditions would be less than that in downhill riding conditions because the highest speeds occur in downhill riding. Consequently, because downhill riding is intuitively one of the more damaging riding conditions if not the most damaging condition for the handlebar/stem assembly owing to the higher speeds, the use of the downhill ride database provided a meaningful direction of maximum damage for the handlebar.

If it was desired to determine the direction of maximum damage that reflected more riding conditions, then the loading for each riding condition would need to be determined together with the time spent in each riding condition. With this information, a record of the loading could be created which represents each riding condition and the proportionate amount of time for that condition. This record could be rainflow counted and used to compute the direction of maximum damage for the wider range of riding conditions using the method presented herein.

Also, because differences in rider weight and ability would be expected to cause differences in the handlebar loading, it was important that the database reflect these differences. However, the riders used to generate the downhill ride database were of similar weight (range 68–79 kg) and all were experienced. Nevertheless, the range of abilities varied markedly as evidenced by the range in the average speed (Table 2). Considering that the direction of maximum damage would be more likely influenced by the rider’s ability than the weight, the downhill ride database did reflect the more important of the two differences.
The loads served as inputs to Eq. (2) which was used to determine the stress history from which cumulative damage was determined. The stress history of eq. (2) is unlikely to occur in service because the analysis ignores the effects of stem attachment. These effects include both assembly stress due to stem clamping and stress concentration due to structural reinforcement of the stem. Their effect on the stress distribution around the handlebar is likely to be non-uniform and specific to a given stem due to the complicated and varied geometry of commercially available stem clamps. Inasmuch as the objective here was to identify a direction of loading that is independent of a particular stem, the stress history computed from eq. (2), which ignores the stem effects, was appropriate.

To analytically determine the cumulative damage, the Walker equation was used to represent the S-N diagram in conjunction with rainflow counting and Miner’s rule. The Walker equation was selected based on an evaluation of how well various equations represented the fatigue data in Military Handbook 5G [6]. To perform this evaluation, power laws were fitted to the S-N data adjusted for mean stress based on the Walker, SWT, Goodman, and Gerber equations [9–11]. Considering all of the stress ratios used to compile the S-N data, the R-squared values were 0.827, 0.774, 0.555, and 0.829 for the Walker, SWT, Goodman, and Gerber equations, respectively. Because the Walker equation fit the data nearly as well as the Gerber equation for all of the stress ratios and slightly better for only the zero and positive stress ratios which better represent the handlebar loading (Fig. 8), the Walker equation was selected over the Gerber equation.

4.2. Importance/interpretation of results

There was enormous variability in the damage calculation (Fig. 6). This large variability was surprising because the riders were of similar height and weight. However, there was some variability in speed as noted above; the maximum speed ranged between 9 and 12 m/s and the average speed ranged between 7 and 10 m/s (Table 2). The rider who produced the most damaging trial was the heaviest and had the fastest maximum and average speeds (highest kinetic energy). Conversely, the least damaging trial was produced by the rider with the least weight, and slowest average and maximum speeds (lowest kinetic energy). These results agree with the notion that rider weight influences the magnitudes of some loads during off-road riding [12]. Obviously, from these differences in damage accumulation, the rider is a major source of variability.

Comparing the direction of maximum damage to Fig. 5 demonstrates that the most damaging angle of loading did not occur most often. The 305° angle of loading occurred the most often and was 17° away from the direction of maximum damage. A bivariate histogram of the rainflow counted stress at 142° (the point of maximum damage) for all 28 trials illustrates that the vast majority of cycles were small in amplitude and had a mean stress near zero (Fig. 8). Calculating the cumulative damage from the respective stress pairs and plotting the result (Fig. 9) illustrates that the most commonly
occurring stress pairs produced only small amounts of damage. Hence, the load direction of the load pairs that occurred most frequently cannot be used to determine the direction of maximum damage.

The direction of maximum damage can be determined approximately from the orientation of the rider on the bicycle however. For a rider 1.75 m tall, the angle measured from the rider’s arms extending to the handlebar in the standing posture was 327°. This angle differed by only 5° from the direction of maximum damage of 322°.

Because the direction of maximum damage determined using the method described herein may have been sensitive to both material and structural properties of the handlebar, this sensitivity was investigated by determining the angle of maximum damage for both a 6061-T6 handlebar and a 2024-T4 handlebar. Based on the finding that the angle of maximum damage for the 2024-T4 handlebar differed by only 1° from that of the 6061-T6 handlebar, it can be concluded that the direction of maximum damage is not influenced by the properties of commonly used handlebars. This conclusion is important because it suggests that the direction of maximum damage identified herein is generally applicable for the design and testing of different handlebars.

The direction of maximum damage differs from the single loading direction determined in a previous study [3]. This previous study also used a database of measured handlebar load components and determined a single direction of loading based on a correlation analysis of the two force components. Single directions were determined separately in both the seated and standing positions. The loading angles were 328° and 310° for the seated and standing positions respectively so that the single loading direction determined based on correlation analysis differed by 12° from that determined herein. Inasmuch as the databases were different between the two studies, it is difficult to state conclusively that the 12° difference in the loading directions is due solely to the differences in the methods used to determine these directions. Nevertheless, some difference would be expected because the methods do not emphasize the same quantities.

Knowing the direction of maximum damage in conjunction with the effects of assembly would enable a design engineer to determine the region of highest stress on the handlebar for a particular stem/handlebar assembly. Because the direction of maximum damage is independent of the stem, it can be used for design and testing of any stem/handlebar assembly. Note however that the region of highest stress for a particular stem/handlebar assembly will not in general coincide with the point of maximum damage determined herein. Both assembly stresses due to tightening of the handlebar stem clamp and stress concentration at the stem clamp/handlebar junction may act in concert to shift the point of maximum damage for a particular stem/handlebar assembly. Consequently, to determine the point of maximum damage for a particular stem/handlebar assembly analytically, the assembly stress and stress concentration would have to be determined and incorporated into the damage calculations.

Although the direction of maximum damage cannot be used to determine the point of maximum damage for a particular stem/handlebar assembly analytically without additional information concerning the effects of assembly, it can be used for single-axis mechanical testing of stem/handlebar assemblies. In the case of testing, the effects of assembly stress and stress concentration are inherent to the assembly and therefore these effects will be reflected in the failure process. Consequently the point of maximum damage could be determined experimentally for a particular stem/handlebar assembly by loading along the direction of maximum damage determined herein and observing the location of fatigue crack initiation.

Since the direction of maximum damage can be used for single-axis mechanical testing of stem/handlebar assemblies, it is useful to compare this direction to that specified in product qualification standards. The ISO-4210 Standard [13] calls for a loading direction of 288°, which coincides with the steering axis of the bicycle and hence differs substantially from the direction of maximum damage determined herein. The testing protocol specified by ISO consists of two stages with loads applied to both ends of the handlebar simultaneously. In the first stage of the test, these loads are applied in opposite directions (i.e. out-of-phase loading) and in the second stage the loads are applied in the same direction (i.e. in-phase loading). The protocol is designed to test both the stem and handlebar. The first-stage loads are directed along the steering axis to apply torque to the stem extension while at the same time avoiding torque about the stem quill. The same loading direction is retained for the second stage of the test to apply bending to the stem extension while at the same time simplifying the testing apparatus. However, this simplification results in loads being applied to the handlebar in a direction that differs substantially from the direction of maximum damage determined herein so that the testing protocol does not represent the loading experienced in off-road cycling.

Rather than relying on a convenient loading direction, the ISO should consider using a method such as that developed herein to determine the direction of maximum damage under a wide variety of conditions for both on-road and off-road cycling. This information could then be used to develop an improved testing protocol for stem/handlebar assemblies. While testing prescribed in ISO-4210 is not use-specific, so that the same test protocol is used for both on- and off-road components, use-specific versions of the same basic test might be advisable if the directions of maximum damage for on- and
off-road cycling differ substantially. This effort would be especially important for fatigue testing of the handlebar because assembly stress and stress concentration in the handlebar due to stem clamping are not axially symmetric (due to complicated stem clamp geometry). Accordingly the loading direction is an important factor in designing a product qualification test consistent with field application.

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References