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Failure analysis of bridle chain used for hoisting in mines

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Failure of engineering components due to presence of defects in the material is common. These defects are either present in the material from the casting stage or get developed during subsequent hot working and thermal treatment operations. Identification of the origins of defects is an important task while analyzing failures where pre-existing defects in the material are the causative factors. A case study and stress calculation on failure of bridle chain links is presented in this paper.

Key words: Bridle chain, chain links, stress point, stress on chain links, tolerance in chains.

INTRODUCTION

The chain is one of the most familiar for mine hoist as well as one of the most useful of mechanical device. It is made up of a series of links fastened through each other. Each link is made of a rod of wire bent into an oval shape and welded at one or two points. The weld ordinarily causes a slight bulge on the side or end of the link (Figure 1). The chain size refers to the diameter, in millimeter (mm), of the rod used to make the link.

Chain is universally employed in hoisting and transmission, and for attaching and securing movable bodies. As a rule, a chain is subjected to heavy loads and must transmit large forces, and upon its ability to withstand the stresses to which it is subjected by its loading may depend on the success of a great mechanical operation, or even the safety of lives (Cage Suspension Gear for Winding in Mines, 2006: Part 4). Chains usually stretch under excessive loading so that the individual links bend slightly. Bent links are a warning that the chain has been overloaded and might fail suddenly under a load. If a chain is equipped with the proper hook, the hook should start to fail first, indicating that the chain is overloaded. In view of these facts, it is surprising that the chain has received scant attention from investigators in the field of elasticity and strength of materials. Aside from two or three scattered memoirs, the theory of the stresses in chain links has been untouched. Experiments have been made, it is true, but these have been for the purpose of determining the ultimate strength of the chain, not for the purpose of testing a theory. Formulas for the loading of chains have been based upon the ultimate strength of the chain when tested to destruction and are thus purely empirical. It may be urged that the present empirical rules are satisfactory, inasmuch as they lead to satisfactory results.

MATERIALS AND PROCESSING

The bridle chains are manufactured from 20Ni2Cr2Mo2 of IS 4432. As per the specification, the effective length tolerance may be ±1 links or 2 links and tolerance on length of each set may be ¼% of effective length or 6mm whichever is less (Cage suspension gear for winding in mines, 2006: Part 4). The steel used in the Manufacture of components of bridle chains shall be produced by acid or basic open-hearth process, acid or basis electric process or

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Figure 1. Bridle chain with short link, intermediate link and end link.

acid-converter process. It shall be fully killed and its content of sulphur and phosphorus shall be restricted to 0.05 percentages individually and both together shall not exceed 0.09% (Cage Suspension Gear for Winding in Mines, 2004: Part 1). The forged component is normalized and machined to the required dimension. The machined component is then case hardened, oil quenched and double tempered before supplying to the customer.

STATIC PROOF LOAD IN BRIDLE CHAINS

Bridle chains shall be subjected to proof load test according to safe working load that consists of the aggregate load suspended on bridle chains and shall withstand the load without permanent deformation Renold publication (1990) on set (Figure 2).

The proof load when applied on 24.2 kN safe working load bridle chains, then one links broke at the maximum load of 99.5 kN, where 50 kN bridle chains have to sustain approx 121 kN proof load. In the chain-manufacturing process, a proof load (between 65 and 80% of breaking load) is applied to all links. Plastic/elastic finite-element analysis (FEA) (Specifications for Case Hardening Steel, 1988) of links has shown that, under a tension equal to proof load, the surface of contact between the two links is permanently deformed. The theoretical point of contact becomes a surface with an elliptical shape, typically one-fourth the size of the chain diameter (Figure 3). The surface of contact has been observed on all chain links inspected.

The photograph of the failed links (Figure 3) shows that the fracture surfaces are consistent with bending. To calculate the fatigue life of chain undergoing bending cycles, the authors propose the following calculation of static load, thereafter stress on bridle chains are derived.

Static working load (safe working load) calculation in bridle chains

In chain assembly each chain is connected to cage hangers at the four corners of the cage and each chain is equally loaded. The actual static load in each of the four corner bridle chains upon which the cage is suspended shall be determined by the following formula

$$P = (5W/2H)x\sqrt{(A^2} + B^2 + H^2)$$

Where,
P= corner chains static load, in kN;
W= total static load of loaded cage and chains etc, in kN;
H= vertical height between the centers of upper and lower shackle pins, in mm;
A= horizontal distance from the centre of the upper shackle pin normal to the line joining the centers of the lower shackle pin at the end of the cage, in mm and
B= half the distance between the centre of the lower shackle pins at the end of cage in mm.

Compression and tensile stress on bridle chain links

A simple chain link consists of semi- circular ends and straight sides connecting them. The theory of stress distribution, for the rings, may also be extended to determine the stress in a chain link. Now consider a chain link subjected to a pull or push through it centre as shown in Figures 4 and 5.

Let,
A= Area of cross-section of chain.
P= Pull on the Chain link.
R=Mean radius of the semi circular ends (Initial radius of curvature).
M= Bending moment on the section L_1 and L_2.
M'= Bending moment on the section CD.
l = Length of the straight portion of the link.
R'=Final radius of curvature.
e_o = Strain in the centroidal layer.
θ =Initial angle subtended at the centre of the bar.
E= Young's modulus.
We know that, the moment for the circular portion L_1 and L_2 (Rajput, 2006).

$$M = M' + \frac{P}{2}(R - R\sin\theta) \qquad (1)$$

Figure 2. Static proof Load sustain in bridle chains at CIMFR laboratory in India.

At straight portion $\mathrm{M} = \mathrm{M'} + \frac{PR}{2}$ and $\mathrm{M'} = \frac{PR}{2}\left(\frac{l+2R}{l+\pi R}\right)$

Also,

$$\mathrm{M{=}E}\ \left(1+\mathrm{e_o}\right)\ \left(\frac{1}{R'}-\frac{1}{R}\right)\ \mathrm{Ah}^2 \qquad (2)$$

$$\mathrm{Ah}^2 = \int \frac{y}{1+\frac{y}{2}}.dA$$

Where, h^2= a constant for the cross-section of the bar (Rajput, 2006).

Comparing Equations (1) and (2), we have

$$\mathrm{E}\ \left(1+\mathrm{e_o}\right)\ \left(\frac{1}{R'}-\frac{1}{R}\right)\ \mathrm{Ah}^2 = \mathrm{M'} + \frac{P}{2}\left(\mathrm{R} - \mathrm{R}\sin\theta\right)$$

Multiplying both sides by $\mathbf{Rd\theta}$ and integrating from $\mathbf{0}\,\mathrm{to}\,\boldsymbol{\pi}/\mathbf{2}$, we get

$$\int_0^{\pi/2} \mathrm{E}\ \left(1+\mathrm{e_o}\right)\left(\frac{1}{R'}-\frac{1}{R}\right)\ \mathrm{Ah^2Rd}\theta = \int_0^{\pi/2} M'Rd\theta + \int_0^{\pi/2} \frac{P}{2}\mathrm{R}^2(1-\sin\theta)\,\mathrm{d}\theta$$

$$\therefore E\int_0^{\pi/2} \frac{R(1+\mathrm{e_o})}{R'}\mathrm{Ah}^2 d\theta - E\int_0^{\pi/2}(1+\mathrm{e_o})\mathrm{Ah}^2 d\theta = \int_0^{\pi/2} M'Rd\theta + \int_0^{\pi/2}\frac{P}{2}\mathrm{R}^2(1-\sin\theta)\,\mathrm{d}\theta \qquad (3)$$

Now, $\left(1+\mathrm{e_o}\right) = \frac{R'}{R}\frac{\theta'}{\theta}$

In this case, initial angle $\theta = \angle VOU = 90°$, however, the final angle $\theta°$ will not be 90° and there will be slight change from 90° (Rajput, 2006).

Slope of the tangent at $\mathrm{V} = \frac{M'l/2}{El} = \frac{M'l}{2EI}$

[Where I=moment of inertia of the section and the values of I for circle= $\frac{\pi r^4}{4}$, for semi-circle = $0.011r^4$ and quarter circle = $0.055r^4$]

$$\int_0^{\pi/2} \mathrm{R}\ \frac{\left(1+\mathrm{e_o}\right)^2}{R'}\ \mathrm{d}\theta = \frac{\pi}{2} - \frac{M'l}{2EI}$$

Substituting in Equation (3), we get

$$\mathrm{EAh}^2\left(\frac{\pi}{2}-\frac{M'l}{2EI}\right)\text{-}\mathrm{E}\left(1+\mathrm{e_o}\right)\mathrm{Ah}.\frac{\pi}{2} = M'R.\frac{\pi}{2} + \frac{PR^2}{2}(\pi-1)$$

Or,

Figure 3. Bridle chains link broke at weld portion.

$$-\mathrm{EAh}^2\,\frac{M'l}{2EI}\text{-}\mathrm{E}\left(1+\mathrm{e_o}\right)\mathrm{Ah}^2.\frac{\pi}{2}=M'R.\frac{\pi}{2}+\frac{PR^2}{2}(\pi-1)$$

Or, $$\mathrm{M'}(\frac{\pi}{2}.\mathrm{R}+\mathrm{Alh}^2)=\frac{PR^2}{2}(1\text{-}\frac{\pi}{2})\text{-}\frac{\pi}{2}EAh^2\mathrm{e_o} \quad (4)$$

Now, $$\mathrm{e_o}=\frac{1}{EA}(\frac{P}{2}+\frac{M'}{R}) \quad (5)$$

Substituting the value of $\mathrm{e_o}$ in Equation (4), we get

$$\mathrm{M'}(\frac{\pi}{2}+\frac{\mathrm{Alh}^2}{2I})=\frac{PR^2}{2}(1\text{-}\frac{\pi}{2})\text{-}\frac{\pi}{2}EAh^2.\frac{1}{EA}(\frac{P}{2}+\frac{M'}{R})$$

Or,

$$\mathrm{M'}(\frac{\pi}{2}+\frac{\mathrm{Alh}^2}{2I})=\frac{PR^2}{2}(1\text{-}\frac{\pi}{2})\text{-}\frac{\pi}{4}h^2P-\frac{\pi}{2}h^2\frac{M'}{R}$$

Or, $$\mathrm{M'}(\frac{\pi}{2}\mathrm{R}+\frac{\mathrm{Alh}^2}{2I}+\frac{\pi}{2}\frac{h^2}{R})=\frac{PR^2}{2}(1\text{-}\frac{\pi}{2})\text{-}\frac{\pi}{4}h^2P$$

(Where k= radius of gyration)

But $I=Ak^2$

$$\therefore M'=\frac{\frac{PR^2}{2}(1-\frac{\pi}{2})-\frac{\pi}{4}h^2.p}{\frac{\pi}{2}R+\frac{lh^2}{2k^2}+\frac{\pi}{2}\frac{h^2}{R}}$$

Multiplying numerator and denominator by $\frac{2}{\pi}$, we get

$$\therefore M'=\frac{P(\frac{R^2}{\pi}-\frac{R^2}{2}-\frac{h^2}{2})}{R+\frac{lh^2}{\pi k^2}+\frac{h^2}{R}} \quad (6)$$

$$\therefore M'=\frac{P(\frac{R^2}{\pi}-\frac{R^2}{2}-\frac{h^2}{2})}{R+\frac{lh^2}{\pi k^2}+\frac{h^2}{R}}+\frac{PR}{2}(l-\sin\theta) \quad (7)$$

[By substituting the value of M' in Equation (1)]; and substituting Equation (6) in Equation (5), we get

$$\mathrm{e_o}=\frac{1}{EAR}[\frac{P(\frac{R^2}{\pi}-\frac{R^2}{2}-\frac{h^2}{2})}{R+\frac{lh^2}{\pi k^2}+\frac{h^2}{R}}]+\frac{P}{2EA} \quad (8)$$

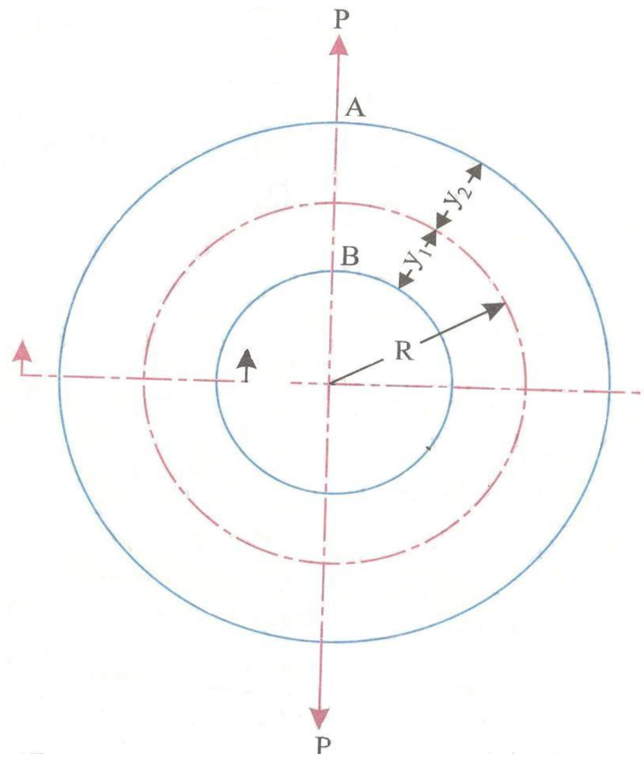

Figure 4. Thickness of bridle chain links.

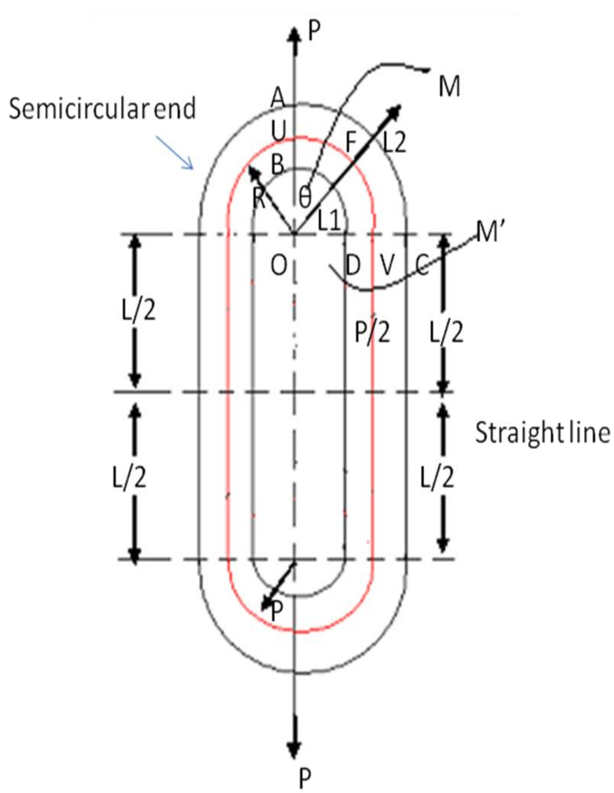

Figure 5. Stress on bridle chain links (Rajput, 2006).

Stress at any layer at distance y from the neural layer in

$$\sigma = Ee_o + E(1+e_o)(\frac{1}{R'} - \frac{1}{R})\frac{y}{1+\frac{y}{R}} \qquad (9)$$

Also, $E(1+e_o)(\frac{1}{R'} - \frac{1}{R}) = \frac{M}{Ah^2}$ (10)

$$\sigma = Ee_o + \frac{M}{h^2}(\frac{Ry}{R+y})$$

Substituting the value of M and e_o, stress due to bending moment.

$$\sigma_b = [\frac{P(\frac{R^2}{\pi} - \frac{R^2}{2} - \frac{h^2}{2})}{R + \frac{lh^2}{\pi k^2} + \frac{h^2}{R}}] + \frac{P}{2A} + (\frac{1}{Ah^2}.\frac{Ry}{R+y}).[\frac{P(\frac{R^2}{\pi} - \frac{R^2}{2} - \frac{h^2}{2})}{R + \frac{lh^2}{\pi k^2} + \frac{h^2}{R}}] + (\frac{1}{Ah^2}.\frac{Ry}{R+y})\frac{PR}{2}(1-\sin\theta)$$

Direct stress due to

$$F = \frac{P\sin\theta}{2A}$$

Result stress, $\sigma_r = \sigma_b + \sigma_d$

$$= \frac{P}{AR}[\frac{(\frac{R^2}{\pi} - \frac{R^2}{2} - \frac{h^2}{2})}{R + \frac{lh^2}{\pi k^2} + \frac{h^2}{R}}] + \frac{PR}{Ah^2}(\frac{y}{R+y})\frac{(\frac{R^2}{\pi} - \frac{R^2}{2} - \frac{h^2}{2})}{R + \frac{lh^2}{\pi k^2} + \frac{h^2}{R}} + \frac{1}{Ah^2}(\frac{Ry}{R+Y})\frac{PR}{2}(1-\sin\theta) + \frac{P}{2A} + \frac{P\sin\theta}{2A}$$

$$\sigma_r = \frac{P}{AR}[1 + \frac{R^2}{2}(\frac{y}{R+y})][\frac{(\frac{R^2}{\pi} - \frac{R^2}{2} - \frac{h^2}{2})}{R + \frac{lh^2}{\pi k^2} + \frac{h^2}{R}}] + \frac{PR^2}{2Ah^2}(1-\sin\theta)(\frac{y}{R+y}) + \frac{P}{2A}(1+\sin\theta) \qquad (11)$$

Calculation of stress in each part of link (Figures 4 and 5) is as shown below.

Stress on a section taken along the line of action of p, where $\theta = 0°$ (Rajput, 2006)

Case I

Outside of ring, at the point A

$$(\sigma_r)A = \frac{P}{AR}[1 + \frac{R^2}{h^2}(\frac{y}{R+y})][\frac{(\frac{R^2}{\pi} - \frac{R^2}{2} - \frac{h^2}{2})}{R + \frac{lh^2}{\pi k^2} + \frac{h^2}{R}}] + \frac{PR^2}{2Ah^2}(\frac{y}{R+y}) + \frac{P}{2A}$$

Or,

$$(\sigma_r)A = \frac{P}{2A}(\frac{l+2R}{l+\pi R})(1 + \frac{R^2}{h^2}(\frac{y_2}{R-y_2})$$ MN/m^2

Case II

Inside of the ring, at the point B

$$(\sigma_r)B = \frac{P}{AR}[1 + \frac{R^2}{h^2}(\frac{-y_1}{R-y_1})][\frac{(\frac{R^2}{\pi} - \frac{R^2}{2} - \frac{h^2}{2})}{R + \frac{lh^2}{\pi k^2} + \frac{h^2}{R}}] + \frac{PR^2}{2Ah^2}(\frac{-y_1}{R-y_1}) + \frac{P}{2A}$$

Or, $(\sigma_r)B = \frac{P}{2A}(\frac{l+2R}{l+\pi R})(1 - \frac{R^2}{h^2}(\frac{y_1}{R-y_1})$ MN/m^2

Stress on a section perpendicular to the line of section of p, where $\theta = 90°$

Case III

At the point C

$$(\sigma_r)C = \frac{P}{AR}[1 + \frac{R^2}{h^2}(\frac{y_2}{R+y_2})][\frac{(\frac{R^2}{\pi} - \frac{R^2}{2} - \frac{h^2}{2})}{R + \frac{lh^2}{\pi k^2} + \frac{h^2}{R}}] + \frac{P}{A}$$

Or, $(\sigma_r)C = \frac{P}{2A} - \frac{PR}{2A}(\frac{\pi - 2}{1 + \pi R})(1 + \frac{R^2}{h^2}(\frac{y_2}{R - y_2})$ MN/m²

Case IV

At inside the ring, at the point D

$$(\sigma_r)D = \frac{P}{AR}[1 + \frac{R^2}{h^2}(\frac{-y_1}{R - y_1})][\frac{(\frac{R^2}{\pi} - \frac{R^2}{2} - \frac{h^2}{2})}{R + \frac{lh^2}{\pi k^2} + \frac{h^2}{R}}] + \frac{P}{A}$$

Or, $(\sigma_r)D = \frac{P}{2A} - \frac{PR}{2A}(\frac{\pi - 2}{1 + \pi R})(1 - \frac{R^2}{h^2}(\frac{y_1}{R - y_1})$ MN/m²

Case V

Maximum stress in straight portion

(i) Bending moment

$$M' = P[\frac{(\frac{R^2}{\pi} - \frac{R^2}{2} - \frac{h^2}{2})}{R + \frac{lh^2}{\pi k^2} + \frac{h^2}{R}}]$$

(ii) Bending stress

$$\sigma_b = \frac{My}{I}$$

(iii) Direct stress

$$\sigma_d = \frac{P}{2A}$$

(iv) Resultant stress

$$\sigma_r = \sigma_d \pm \sigma_b$$

RESULTS AND DISCUSSION

The defect described above is a mechanical defect and got created when samples were brought to the laboratory for examination, visual and stereo-binocular observations revealed surface defects in samples (Metals handbook: Failure analysis and prevention, 1975). While the nature of the defect was clearly identified, it was still not established unambiguously whether or not the defects were developed during testing of the components. Proof load when applied on chain (Figure 2) then the stress is evenly distributed over the entire cross-section at point B (inside portion). The more stress occurs at point B when all chain links are connected to each other. Stress when exceeds certain strength limits (Sei and Goenka, 2001) of the link, links DC portion started to increased due to more tension on it and finally broke at welded portion (Figure 3) and result in permanent deformation.

(i) The stress between the point A and B, maximum stress acts at point B and the minimum at point A (Gupta, 1989).
(ii) The maximum shear stress is at θ (OL_2)= ±45° from θ (−2θ =90°).
(iii) The normal stress maximum is at θ(OA) = 0° from θ (-2θ = 0°).
(iv) The normal stress minimum is at θ(AB) = 90° from θ (-2θ = -180°).

The strength of a chain link is 1.63 times the strength of the bar from which it is made. The strength referred to is the breaking, or tensile, strength. It is never safe to strain to anywhere near the breaking point, because every time a piece of metals is strained to a point beyond its elastic limit it is permanently stretched and weakened (Lynch, 2003). For this reason, it is never considered advisable to strain a chain to more than one-half the amount shown by the method given for computing the tensile strength.

Conclusion

1. Equation (11) gives the resultant stress in any section along the curved portion of the chain link.
2. On the straight portion of the chain link the bending moment M' will remain constant. The bending stress in the straight portion and resultant stress, direct tensile stress $\frac{P}{2A}$ will be added to bending stress (Ferdinanl, 1962).
3. The case study illustrates an example of inherited defects in the material.
4. Chain can fail mechanically in the following ways:

i) Overload- should never happen;
ii) Fatigue- should try to design around this
iii) Wear- the normal mode

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