NOTES ON
THE POSSIBLE BAUSCHINGER EFFECT
ON THE REINFORCEMENT-STEEL
IN A CONTINUOUSLY REINFORCED
CONCRETE PAVEMENT

by

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Comment: These notes have been prepared for reference purposes in connection with the current research program in continuously reinforced concrete being conducted for the Pennsylvania Department of Highways by Lehigh University, under the sponsorship of the Pennsylvania Department of Highways, and the American Iron and Steel Institute.
The most valuable evidence concerning the plastic deformation of materials comes from experiments made on single crystals. These crystals deform plastically by means of translational slip, in which parts of the crystal slide in a certain direction along some weak crystallographic planes across the neighboring parts when the shear stresses at those planes reach a critical value.\(^1\),\(^2\).

\[\begin{align*}
\sigma & \quad \tau \\
\text{(a)} & \quad \text{(b)}
\end{align*}\]

Fig. 1 (a) shows a single grain with axial stress and shearing stress acting along the slip planes. (b) shows the atoms from which the crystal is made, near the slip planes.

As shown in Fig. 1, under some axial load \((\sigma)\) the shearing stress \((\tau)\) along the weak plane reaches a high enough value to force the atoms to shift one place along the slip plane, causing plastic deformation in the crystal, while the atoms still hold each other as tightly as before.

1. Investigations have shown that the slip direction (weak crystallographic plane) is almost always that along which the atoms are most closely packed.

2. Crystals may deform, not only by slip, but by mechanical twin formation. However, under normal conditions, iron and alloyed ferrites do not deform by twinning. They can be twinned by impact at room temperature, or by slow deformations at lower temperatures.
A steel bar is a conglomerate of millions of microscopic crystalline minerals. When an axial load, say tension, is applied to it, shear stresses will develop along planes making angles to the applied load. Those stresses will be zero at planes perpendicular to the applied load, and maximum at planes which are at angles of 45° to the applied load. The crystal grains in the specimen are randomly located, therefore the weak crystallographic planes in each will be differently oriented with respect to the greater or critical shear stresses. Under increased loading, slip takes place along the slip planes which coincide with the greater shear stresses. The crystals where slip planes are more favorably located with respect to the critical shear, deform only elastically under the subjected axial load. The elastic deformations of individual grains add up to cause the total elastic deformation, and the plastic deformations of individual grains add up to cause the total plastic deformation (yielding) of the specimen.

As yielding continues, the slip planes of the neighboring grains which lie in different directions, tend to hinder the movements of each other, the sliding plates tend to dig into each other. Thus the resistance against slip gradually increases, strengthening the steel bar. If, at this stage, the specimen is unloaded and then after a while reloaded, a stress-strain diagram, as shown in Fig. 2, is obtained.

3. Slip starts from structural irregularities in the crystal.

4. The time which elapses between unloading and reloading has a marked effect on the amount of increase of the elastic strength. Tests made by P. Ludwik showed that: "a 1 percent stretched electrolytic iron, after lying a half-hour had its yield point increased over 13 percent; after 24 hours a 25 percent increase was noticed, and after three months a 33 percent increase."
The cold working which the material undergoes by the initial load application increases its elastic strength in tension from $\sigma_1$ to $\sigma_2$, and decreases its ductility.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{stress_strain_diagram.png}
\caption{Stress vs. Strain}
\end{figure}

Fig. 2

It has been mentioned earlier, that while the loads above the yield point cause permanent deformations in many of the crystals, several which are more favorably oriented are only deformed elastically. When the load is removed, the grains which have only elastic strains tend to shorten and regain their original shape. In doing so they compress their permanently deformed neighbors. This action causes tension in the elastically strained grains, and compression in the plastically strained ones. These residual compressive stresses eat up some of the original compressive elastic strength of the material. Afterwards, if a compressive load is applied to the bar, it is observed that the strains increase considerably under relatively light loads, because the grains under residual compressive stresses can stand only a load equal to the original yield point load minus the residual compression before yielding. All this indicates that when steel is loaded beyond its yield point in tension, its elastic strength is raised in tension and lowered in compression, and that the ductility of it is diminished. The reverse of this behavior, where the specimen is first loaded beyond its yield point in compression, can be explained in the same way. Then its elastic strength is raised in com-
pression, but lowered in tension\(^5\).

Due to seasonal temperature variations, the steel bars at a crack in a continuously reinforced concrete pavement may yield in tension due to cold weather contraction and then yield in compression when the weather becomes warmer and the pavement expands.

When this cycle is repeated due to yearly temperature changes, the resistance of the bars in relation to their deformation may, due to this "Bauschinger Effect", vary as shown in Figure 3.

In Fig. 3, the solid line shows the effect of the initial tension in a steel reinforcing bar, starting from zero deformation and resistance. After yield, if the bar is released, the resistance drops to zero but some deformation remains. Then if the bar is loaded in compression, as shown by broken line, and is again released and loaded in tension, the effect as indicated by the dotted line, shows that the steel does not resist as much to deformation as it did initially. This may result in increased elongation before the steel can utilize its original yield strength.

Also, it must be observed that in the broken and dotted line curves, there is no sharp yield point as in the solid line curve, and stresses are proportional to strains only for relatively low values. Therefore one must be reserved in assuming constant modulus of elasticity.

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5. For the first time in 1881, Johann Bauschinger published the results of a series of experiments which demonstrated this behavior of ductile materials which is sometimes called "THE BAUSCHINGER EFFECT".
Resistance Against Elongation

Initial yield

Final tension

Initial tension

0 is the initial point of no deformation and no resistance

Deformation Due To Shortening

Deformation Due To Elongation

Resistance Against Compression

Figure 3
CONCLUSION

The decrease in the elastic compressive strength of the steel probably does not have an appreciable effect on continuously reinforced concrete pavements because concrete is strong enough to take the thrust. But if the elastic strength of the steel in tension is lowered, it may mean greater strains, therefore wider cracks in the pavement under relatively smaller forces.

It has been thought that in predicting the future action of the pavement cracks under shrinkage and temperature effects, experimental information about the behavior of the reinforcing steel under cycles of load going from tension yield to compression yield can be quite useful.

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