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Residual stresses in structural steel shapes--a summary of measured values, February 1973 (74-12)

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ABSTRACT

A summary is presented of thermal residual stresses and their distributions measured on various structural steel shapes. The longitudinal residual stresses are shown in figures drawn to scale suitable for direct use by researchers and designers. Over eighty different shapes are included comprising hot-rolled (wide-flanges, angles, tubular shapes and rails) and welded sections (H-, L-, T-, and box shapes). The H-sections are in the majority, ranging in size from W4x13 to W14x730 for hot-rolled sections, and from H7x21 to H24x1122 for the welded sections. The major portion of the reported results comes from various research projects conducted at Lehigh University during the past two decades. Some results come from research conducted elsewhere.

1. INTRODUCTION

Residual stresses have been studied theoretically and experimentally for many years. However, it was only in the past two decades that it was realized that residual stresses are a major influence in the behavior and strength of structural members. In particular, their influence on the strength of compression members, such as columns, has been widely recognized and has had a major impact on the formulation of design criteria of many specifications. In general, the presence of residual stresses will influence the strength in stability, fatigue and fracture; in some situations, however, their presence may improve the strength.

Residual stresses exist in almost all structural shapes, whether rolled, welded or cold-straightened. While it would be possible theoretically to remove residual stresses from a member, for instance by stress relieving, this is normally not practical nor economical; however, it is possible to achieve a control over their influence.

The residual stresses in several structural sections have been determined both theoretically and experimentally as part of various research projects at Lehigh University under the technical guidance of the

Column Research Council. Limited information is also available from research conducted elsewhere. However, in utilizing the available information two difficulties arise: (i) A significant portion of the available results does not exist in the published literature, and (ii) The results found in the published literature are in most cases drawn at too small a scale to be of direct use, even though they serve the purpose for preliminary investigations.

The purpose of the work presented here is an attempt to fill part of this gap. The first objective is to review previous experimental investigations and to assemble the results in a systematic manner following a standard figure format. The work is concerned primarily with longitudinal residual stresses in structural sections of hot-rolled (wide flanges, angles, rails and tubular shapes) as well as built-up sections (H-, L-, T- and box shapes). The figures will permit researchers and designers a better access of available information and can also be utilized whenever tests are planned to provide design data or verify theoretically derived design procedures, by providing definitive information.

2. FORMATION OF RESIDUAL STRESSES

The mechanics involved in the formation of residual stresses is quite complex. In general, residual stresses are formed in structural members as a result of plastic deformations. These plastic deformations may be due to cooling after hot-rolling, welding or oxygen-cutting (thermal residual stresses); or they may be due to fabricating operations of the finished cold product such as in cold-straightening (deformational residual stresses). Since residual stresses are internal stresses which exist in an externally unloaded member, the stresses must be distributed through the cross section such that they satisfy all equilibrium conditions. (29)

Plastic deformations due to cooling result from the fact that some parts of the shape cool more rapidly than others (differential cooling), thus causing plastic deformations in the slower cooling portions. For instance, in rolled wide-flange shapes it is obvious that the flange tips would cool more rapidly than the juncture of flange and web. The cooling portions will begin to gain stiffness and the strains created by the differential cooling will result in internal residual stress patterns. In the same manner, welding or oxygen-cutting operations introduce residual stresses as a result of the localized heat

input. In general, the slower cooling portion will usually contain tensile residual stresses which must be balanced by compressive stress in the remaining cross section. (29)

Residual stresses introduced due to cold-straightening result from deformations exceeding the elastic limit in the cross-section of the member. The nonuniformity of the cooling process of rolled steel sections will usually result in cooled specimens of unacceptable out-of-straightnesses. Such distortions are corrected by cold-straightening at the steel plant either by gagging or rotorizing, thus introducing a redistribution of stresses. Residual stresses in straightened members are quite different from those measured in the as-rolled member. (37) The residual stresses in the flanges are more randomly distributed and are usually significantly lower than the thermal residual stress existing in unstraightened sections. Residual stresses due to cold-straightening have not been included in this study.

3. MEASUREMENT OF RESIDUAL STRESSES

The residual stresses presented in this study have been measured using the "Sectioning Method". This method has been used for decades to measure residual stresses in structural-steel members. The method has proven itself adequate, accurate and economical if proper care is taken in the preparation of the specimens and the procedure of measurement. A detailed description of the procedure to carry out such measurement is given in Ref. 36.

The method of sectioning is based on the principle that internal stresses are relieved when the specimen is cut into many strips of smaller cross section. The method is best applied to members when the longitudinal stresses alone are important. The method can also be applied to measure the residual stress distribution through the thickness by employing the "slicing" technique. The steps in the sectioning and slicing process are illustrated schematically in Fig. 1.

4. SCATTER OF RESIDUAL STRESSES

The most important factors that cause variation or scatter of residual stresses between different steel members are the geometry, steel grade and the fabrication procedures.⁽³²⁾ However, due to uncontrollable factors, the residual stress distributions may vary between different members of the same geometry and manufacturing condition.

The variation of residual stresses measured on six European heavy shapes of the same nominal size, but rolled at three different mills (Belgium, Germany and Italy), is shown in Fig. 2. The specimens were chosen to furnish a good representation of the population of columns obtainable in Europe.⁽³⁵⁾ As shown in the figure, the variation of residual stress distribution appears to be reasonably small.

The variation of residual stresses as measured at different positions on the same specimen are shown in Fig. 3 for a light rolled wide-flange shape and for a heavy welded H-shape. In both cases, the variations are also seen to be small.

The effect of yield strength on the residual stress distribution is not as great as the effect of geometry.^(29,30) Residual stresses in light rolled

wide flange shapes made of four different steel grades and a heavy welded shape made of two different steel grades are shown in Fig. 4. Except for the shape of steel grade ASTM 514, the residual stresses in the flanges are similar; there are some variations in the web, but no greater than that for any group of the same steel. ASTM 514 is a quenched and tempered steel; it would be expected that steels that require heat treatment after rolling will exhibit a different residual stress pattern.

In conclusion, as indicated in Figs. 2 to 4, the variation between residual stress distribution in different members of the same geometry and manufacturing procedure appear to be fairly small. This observation is in agreement with previous investigations. (4,32) Hence, the residual stress distribution in a particular section may be predicted from data obtained on a similar shape fabricated under the same manufacturing conditions.

5. RESIDUAL STRESSES IN HOT-ROLLED SHAPES

Hot-rolled shapes have been used in construction rather extensively in the past and are still the dominant structural shapes in use. Studies on the strength of hot-rolled columns in the late 1940's began with measurements of residual stresses. Thereafter, extensive experimental and theoretical studies of thermal residual stresses have been carried out. (2,5,13) Most of the results reported in this paper come from various research projects at Lehigh University conducted under the technical guidance of the Column Research Council.

The principal factors which influence the magnitude and distribution of residual stresses in rolled sections are the shape of the cross section, rolling temperature and cooling conditions. (2) The nature and formation of residual stresses can readily be visualized by considering the cooling process. The flange tips and the web of a relatively light wide-flange section, for example, can be visualized to cool more rapidly than the central flange areas and the web-to-flange juncture; consequently, the former areas in most cases result in compressive residual stresses whereas the latter areas result in tension. While a similar conclusion can also be made for heavier shapes, the cooling process in such

shapes is not as straightforward to understand as it is in light shapes. In heavy members, the mechanics regarding the combined effects of the heat transfer of the surface area and the internal conductivity of the volume of the member are quite involved. Experimental investigations on heavy shapes have indicated that the residual stresses vary significantly through the thickness. Also, the residual stresses tend to increase with increasing size of the member. (2)

A series of residual stresses are presented in Figs. 5 to 57 for various rolled wide-flange shapes, angles, tubular shapes and rails. For each particular case the source reference is also given. The residual stresses for wide-flange shapes are in the majority and the shape sizes range from a very light shape W4x13 to the heaviest rolled shape, the W14x730 "jumbo" shape.

6. RESIDUAL STRESSES IN WELDED SHAPES

Welded built-up shapes are used frequently as structural members. The most common shapes currently produced are the H and box shapes. The versatility of the method of manufacture has encouraged the fabrication of various forms of cross sections. From the mid-1950's on, attention has been directed to residual stresses set up by the welding process. The first studies were on welded plates and shapes of medium size. (28,31) An extensive research program on residual stresses in heavy welded plates and shapes underway at Lehigh University, is nearing completion.

Generally, the magnitude of residual stress is independent of the grade of steel, the welding geometry and the welding conditions. Recent investigations have shown that while welding has a significant influence on the overall distribution of residual stress in small and medium-size shapes, the effect appears to be local in heavy shapes. (3) As in rolled shapes, the residual stress in heavy shapes vary significantly through the thickness.

The residual stresses in several welded H-shapes, box shapes and miscellaneous shapes are given in Figs. 58 to 88.

7. SUMMARY

This report summarizes the results of a long-term investigation on thermal residual stresses measured in various structural shapes. The longitudinal residual stresses of over eighty different shapes are presented following a standard figure format suitable for direct use by researchers and designers. Residual stresses due to cold-straightening have not been included in this report. The sections presented include hot-rolled wide-flanges, angles, tubular shapes and rails, and also, welded sections of H-, L-, T-, and box shapes. The residual stresses were measured by the sectioning method.

The most important factors that cause variation or scatter of residual stresses between different members are the geometry and the fabrication procedure. The effect of yield strength on the residual stress distribution was found to be small. The distribution measured at various sections along the length of a particular member, or in different members of the same geometry and manufacturing procedure appear to be small. For all practical purposes, the thermal residual stress distribution in a particular section may be predicted from data obtained in a similar shape fabricated under the same manufacturing conditions.

8. ACKNOWLEDGMENTS

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Fig. 1 Principle of the Sectioning Method for Residual Stress Measurements

Fig. 2 Residual Stresses as Measured in Six Hot-Rolled Heavy Wide-Flange Shapes

Fig. 3 Residual Stresses Measured at Different Positions

Fig. 4 Effect of Yield Strength on Residual Stress Distribution

Figs. 5 through 57 Residual Stresses in Hot-Rolled Shapes

Figs. 58 through 88 Residual Stresses in Welded Sections