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And much, much more!

Manufacturing Processes Influence Fatigue Life

Software for predicting fatigue life must consider the effects of various processes on performance.

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Fatigue expectations traditionally have been formulated during the experimental stage of product development to evaluate unexpected failures seen in proving-ground vehicle testing or to define procedures for accelerated laboratory bench tests. A key feature of the modern durability design process is integration of computing methods with finite-element analysis (FEA) to predict durability early in design. In the automotive industry, early evaluation of fatigue performance can increase reliability and reduce product development time.

Usually a durability analysis includes three steps: define the load environment, define a relationship between load and stress/strain state, and predict the lifetime of the structure. Automotive fatigue designs have been based on the nominal stresslife (S-N) curve, modified by empirical coefficients to account for mean stress, surface finish, geometric features, multiaxis loading behavior, residual stresses, and cumulative damage that influence fatigue behavior. This approach, applicable only to nominally uniaxial elastic stresses, is inadequate for integration into a design procedure using local stress tensors determined by FEA. The local uniaxial ε-N approach is more consistent with metal fatigue physics in accounting for notch plasticity, but this method does not consider surface conditions encountered with cast or forged parts. According to Fiat engineers, new methods to overcome these limitations are needed for suspension and engine parts that experience multiaxial stress from combined loading and geometrical effects.

For fatigue with multiaxis loading, methods can be divided into empirical and theoretical approaches. Empirical approaches use data from experimental tests of bending combined with torsion. In the theoretical approach, damage is related to a physical parameter.

New fatigue-life prediction software named PRINCE (for PRediction INtegrated with Code for finite Elements) is fully integrated with popular FEA commercial software at Fiat (Figure 1). The criteria selected can compute crack initiation life of a component in both high cycle and in the finite life range of more than 10^5 cycles. This is a common fatigue life point desired in accelerated bench tests.

PRINCE evaluates the fatigue safety coefficient (FSC) and life for the FEA stress tensor for each loading event of the time history, computed by FEA, and the S-N curve's material fatigue data constants available from conventional tests dissected from actual components allow determination of surface effects from the specific manufacturing

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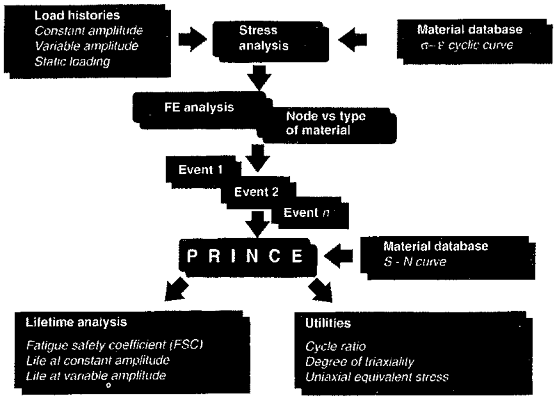

Figure 1. Flow chart of the integrated FEA-FLP procedure

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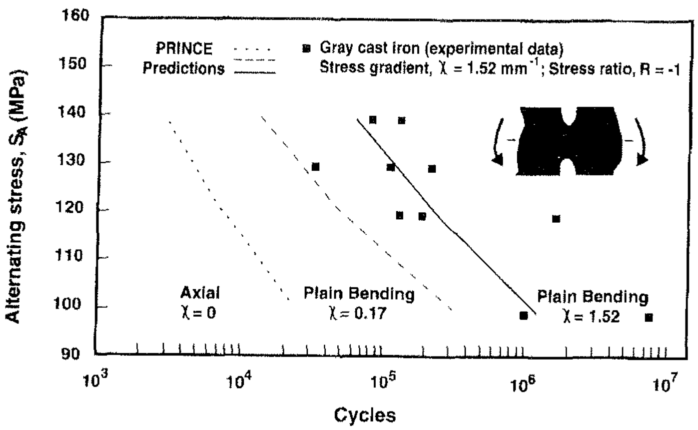

Figure 2. Influence of material data on fatigue life prediction

process on fatigue properties. PRINCE can relate different fatigue properties resulting from the manufacturing process to specific areas of the part. This feature improves durability analysis on components manufactured with material strongly affected by stress gradients.

To confirm predictions of stress gradient effects on fatigue, experimental data are important. Predicted fatigue life for a notched gray iron shaft with a relative stress gradient of $1.52 mm^{-1}$ under rotating bending loads can be as much as two orders of magnitude too conservative (Figure 2). When constants of the S-N curve are related to stress gradient, computed fatigue life shows good agreement with experimental results.

Fatigue properties related to production processes

In high-volume production, manufacturing processes that give the final geometry of the part without the burden of machining operations help reduce costs and cycle time. For example, connecting rods, crankshafts, suspension arms, and steering knuckles that are cast or hotforged need machining only on small areas serving as mating surfaces with other parts of the system. Frame side rails fabricated from sheets are blanked, formed, and drawn without machining.

Connecting rod — Connecting rods for production engines mainly are cast of nodular or malleable irons, or forged from quenched and tempered carbon or microalloyed steels. Applications of sinter-forged powder metal materials are increasing, especially in the United States.

Surface features of connecting rods strongly affect fatigue performance. Critical regions are the machined areas at the two ends and the unmachined surfaces on the column and exteriors of the ends. Since it is difficult to reproduce the surface of the column (in roughness and metallurgical structure) on test specimens, Fiat used actual rods to get a family of S-N curves with stress cycle ratio related to operational loads. Since fatigue performance is strongly affected by surface and internal defects peculiar to the selected manufacturing process, a relationship between maximum defect size and the lower bound endurance limit at 10^8 cycles must be defined (Figure 3).

Front suspension arm — Suspension arms are fabricated by welding together previously stamped, thin, high-strength low-alloy (HSLA) steel sheets by hot forging various steels or by casting nodular iron. The latter two processes permit more parts integration compared to weldment arms. Critical areas are shot-blasted, trimmed of flash, blanked for holes, and/or machined.

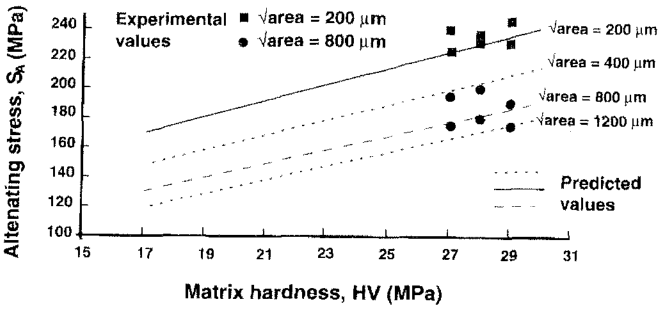

Figure 3. Influence of internal defects on specimen fatigue behavior

For suspension arms of hot-forged steel, surface defects of blank surfaces reduce fatigue strength by 30% from that of the machined areas (Figure 4). Further reductions in fatigue strength occur after trimming flash or blanking holes in forged arms. Test specimens were sections of actual arms. Nodular cast iron arms are differentiated from steel arms by reduced notch sensitivity. Improved fatigue behavior on blank areas compared to machined ones arises from the compressive residual stress produced by shot blasting. Application of fatigue strength reduction factors based on surface features of steel can cause erroneous conclusions in FLP analysis of cast irons.

Truck frame side rail — On frame side rails constructed from HSLA steel sheet, fatigue damage of the structure often is localized in unused holes that are used only in some applications. They act as fatigue notches. A second critical region is the blank profile of the side rail that is subjected to high stresses during normal service loading.

The reduction of the fatigue limit of a notched component can be computed from the notch geometry and the material characteristics. For machined notches such as drilled holes, tests show that the fatigue stress concentration factor, K_f is less than the tensile stress concentration factor, K_t. Tests on HSLA steel sheet specimens with different mechanical properties show that $K_f = 0.7 K_t$ for machined holes, independent of loading mode and tensile properties of the material (Figure 5).

Local geometric discontinuities produced by punching holes increases greatly the actual K_t value compared to that computed from the notch's nominal geometry. For axial loading, results indicate $K_f \approx 1.5 K_t$ for material with ultimate tensile strength, R_m up to 600 MPa, while $K_f \approx 2.5 K_t$ for materials with higher tensile strengths.

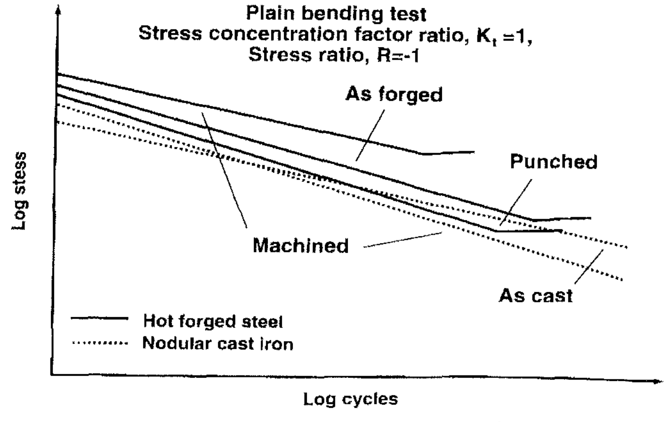

Figure 4. Changes in fatigue properties with manufacturing processes

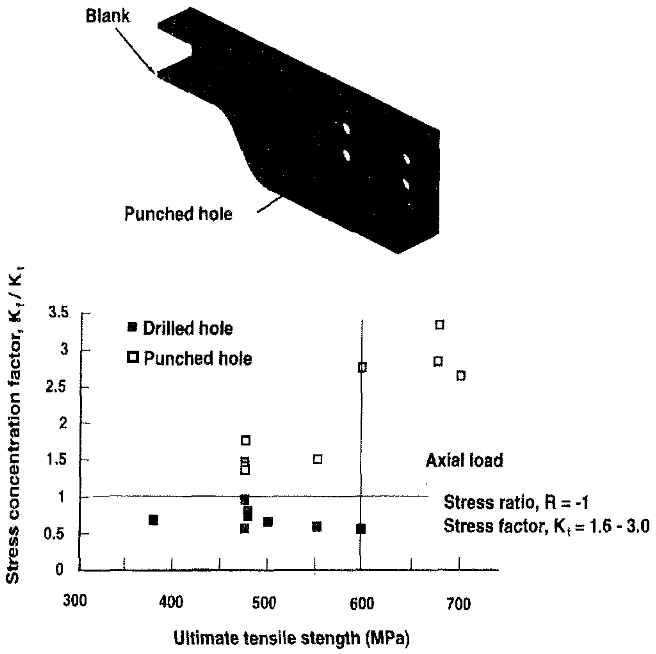

Figure 5. Fatigue notch sensitivity of truck frame side rail with punched hole

Fatigue behavior of this material shows the same trend even in blanked areas on the side rail's periphery. Tests were performed on two HSLA steel sheets, FeE42O and FeE490, in plain bending. FeE420 has a yield stress, R_p of 420 MPa and ultimate strength, R_m of 530 MFa, and FeE490 has R_p of 490 MPa and R_m of 600 MPa. The higher notch sensitivity of FeE490, which increases tensile and fatigue properties in machined conditions, drastically reduces fatigue performance in blanked conditions (Figure 6).

This is another example showing the importance of knowing the effects of various processes on the fatigue performance of a material to avoid significant errors in predicting the fatigue life of parts made from that material.

These examples of different automotive parts emphasize how reliable fatigue design demands integrating into the CAE environment ways of accounting for the influence of various factors on the fatigue performance. Without knowing the effects of actual manufacturing processes on fatigue properties of selected materials, the results from improved fatigue life prediction software such as PRINCE will not be reliable.

Information was provided by **Adriano Blarasin** and **Tommasa Giunti**, Centro Ricerche Fiat.

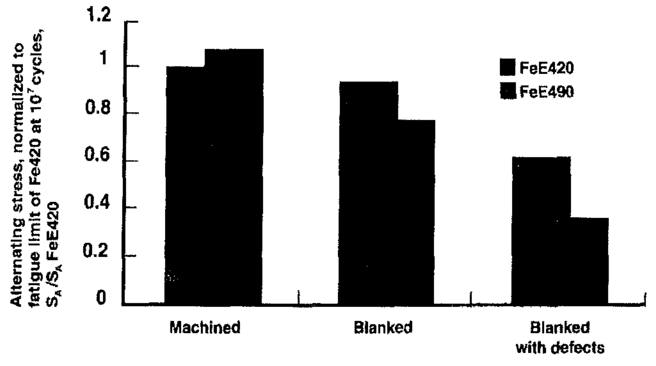

Figure 6. Influence of surface defect of fatigue in blanked area