Performance Prediction of Roll-Over Protective Structures (ROPS) Through Analytical Methods- SAE J1215

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1. Purpose—To discuss an analytical approach to predicting ROPS structural performance that is an alternative to the destructive testing recommended in SAE J1040.

2. Scope—This report discusses the use of specialized analytical procedures that can be used to predict the structural behavior of ROPS and machine frame systems subjected to testing as described in SAE Recommended Practice J1040. For practical reasons, these complex calculations require the use of computerized methods. Specific approaches that are thought to be essential to preparing accurate analytical predictions are described. The importance of an experienced ROPS analyst is reviewed.

The use of analytical procedures to predict the performance of ROPS is especially desirable for ROPS designed for installation on very large off-road machines, where problems of testing are extraordinarily great, and for predicting the effects of changes to proven ROPS designs before retesting.

This report also covers the use of these analytical techniques as ROPS design tools.

3. Technical Approach—The predictive analysis of ROPS-machine frame structural behavior when subjected to load and energy requirements of the type recommended by SAE J1040 requires the use of methods that are not presently routine or widely used in analysis of off-road machine structures. The analysis of ROPS is conveniently divided into two distinct areas of computation, both of which should be treated in the same computer program.

First, when subjected to loads that do not cause any of the structure's elements (beams, plates, connections, etc.) to exceed the elastic limits of the material used, the structure behaves as expected when analyzed using more routine engineering approaches. Thus, the analysis of ROPS within the elastic limits of the material of construction is straightforward. Many excellent computer programs are available for elastic analysis of operator protective structures.

The second area of ROPS analysis is encountered when the loads received by the structure induce stresses which exceed the elastic limit of an element and that element begins to be permanently deformed. This element is now *going plastic* and the behavior of that element will no longer follow the behavior predicted by considering only the elastic properties of the material. The analytical procedure used to predict the ROPS behavior when subjected to loads that cause beams, plates, or connections to exceed their elastic capability and to begin to deform plastically must consider the plastic properties of the material.

The efficient design of energy absorption ROPS usually results in several elements of the structure exhibiting plastic behavior. In some designs, portions of the machine frame might also behave plastically. The analytical approach used to predict ROPS performance should, therefore, consider the following:

3.1 **Definitive Modeling of the ROPS and Machine Frame**—ROPS are usually constructed of square or round tubing with a top plate; ROPS cabs are often constructed with plates and commonly available types of beams, such as tubing, channel, angle, T-section, and Z-section. The analysis of the ROPS and machine frame may require both plate and beam elements of various types of cross sections to establish a realistic model. In the plastic analysis, the formulation of a beam element varies with the type of cross section.

3.2 **Prediction of Force Versus Deflection for Load Inputs**—These calculations must predict performance in both the elastic and plastic ranges of the material. Prediction of local and column bucklings of beam elements must also be included in the analysis. The stability of an element may significantly influence the force-deflection relation of the structural system. The locked-in stresses realized from a loading should be taken into account on the subsequent loading if the ROPS is to be evaluated under multiple, sequential loadings.

3.3 **Update of Structure Geometry During Deflection**—Since many ROPS systems exhibit large deflections, especially during side loading, the effect of this deflected geometry must be considered in the computations. Boundary conditions may change, especially when gaps are built into the

ROPS. They must be updated in the analysis.

3.4 **Analysis of Joints**—Joint details are often not considered in the main analysis program of ROPS. The integrity of a joint, if questionable, must be analyzed, and it may be carried out separately from the main analysis.

3.5 **The ROPS Design/Test Experience of the Analyst**—Since the modeling of the ROPS and the machine frame will strongly influence the accuracy of the performance predictions, it is important that the analyst have a thorough background in the design and correlation with test performance of ROPS-machine frame systems that exhibit elastic/plastic behavior. Experience will allow the analyst to judge the necessity of detailed modeling in areas that may go plastic and will allow more general modeling in areas of low stress. The ability of the analyst is usually the largest variable affecting ROPS structural performance predictions.

The above statements indicate the minimal requirements for accurate analysis. Analytical approaches developed by several different researchers have these qualities in common but may differ on the detailed approach to satisfying a particular analysis area. For example, the determination of stress at a known strain value as the material exceeds its plastic limit can be treated by several methods. The important fact is that material plasticity is accounted for in a manner that produces accurate predictions. Use of the actual stress-strain properties of the material used for construction of the ROPS and machine frame will increase the accuracy of the force-deflection curve prediction. Another facet of some ROPS analysis computer programs is the use of a graphical display of the deformed shape of the structure under loading. This graphical plotting capability is also useful to verify the input geometry.

The use of analysis to predict ROPS structural performance has many additional benefits. It is often evident from the results of the initial analysis of a ROPS design that minor changes in material thickness or location could produce a superior protective structure. The analyst can also explore the probable effects of changes in material properties from one material lot to another. The ROPS structural performance can be determined in simulated load applications different than those specified in SAE J1040. In short, proper analysis permits more convenient study of behavior under various loadings than does testing.

A benefit presently exists in designing ROPS for retrofit applications which often present no opportunity for destructive static performance testing. The available analytical procedures allow confident ROPS design for retrofit applications. The future benefits of ROPS performance analysis are significant. Reduction in the need for destructive performance testing may be possible as the skill of ROPS analysts increases and as more use of analysis occurs.

The following References describe computer programs that have been used by ROPS designers and are said to produce satisfactory predictions of ROPS performance. These programs appear to have reached a satisfactory degree of development and sophistication. It is believed that further enhancements can be made within the state of the art.

No endorsement by SAE is intended by including these References: the user should determine the capability of the computer program.

1. User's Guide to Elastic Plastic SAP, Lockheed Propulsion Company Document No. 684-7-6568R1 dated August 1975. (Available to the public from U.S. Army Mobility Research and Development Command, Ft. Belvoir, VA.)

2. SDRC-SAGS (Static Analysis of General Structures, Version III) and SDRC-LAGS (Limit Analysis of General Structures, Version II). (These are proprietary programs developed by Structural Dynamics Research Corp., Cincinnati, OH.)

3. SAP ROPS (a proprietary program developed by International Harvester Co.).

4. Plastic CANOPY, U.S. Bureau of Mines, Pittsburgh, PA. (Available to the public through the U.S. Bureau of Mines or through Woodward Associates, Inc.)