MACHINE DESIGN

Machine Design (ISSN 0024-9114) is published semimonthly by Penton Media, Inc., 1100 Superior Ave., Cleveland, OH 44114-2543. Copies not qualified for domestic requester circulation: one year, $105; two years, $165. Permission to photocopy is granted for users registered with the Copyright Clearance Center (CCC) Inc. to photocopy any article, with the exception of those for which separate ownership is indicated on the first page of the article, provided that the base fee of $1.25 per copy of the article, plus $.60 per page is paid to CCC, 222 Rosewood Dr., Danvers, MA 01923 (Code No. 0024-9114/00 $1.25 + .60).

Permission to reprint: Barbara LoSchiavo; Purchased reprints: Judy Dustman (216-696-7000, ext. 9607); Advertising Materials: Advertising Dept., Machine Design, 1100 Superior Ave., Cleveland, OH 44114-2543, 216-696-7000. Inserts should be sent to Machine Design, Penton Press, 680 N. Rocky River Dr., Berea, OH 44017-1691.

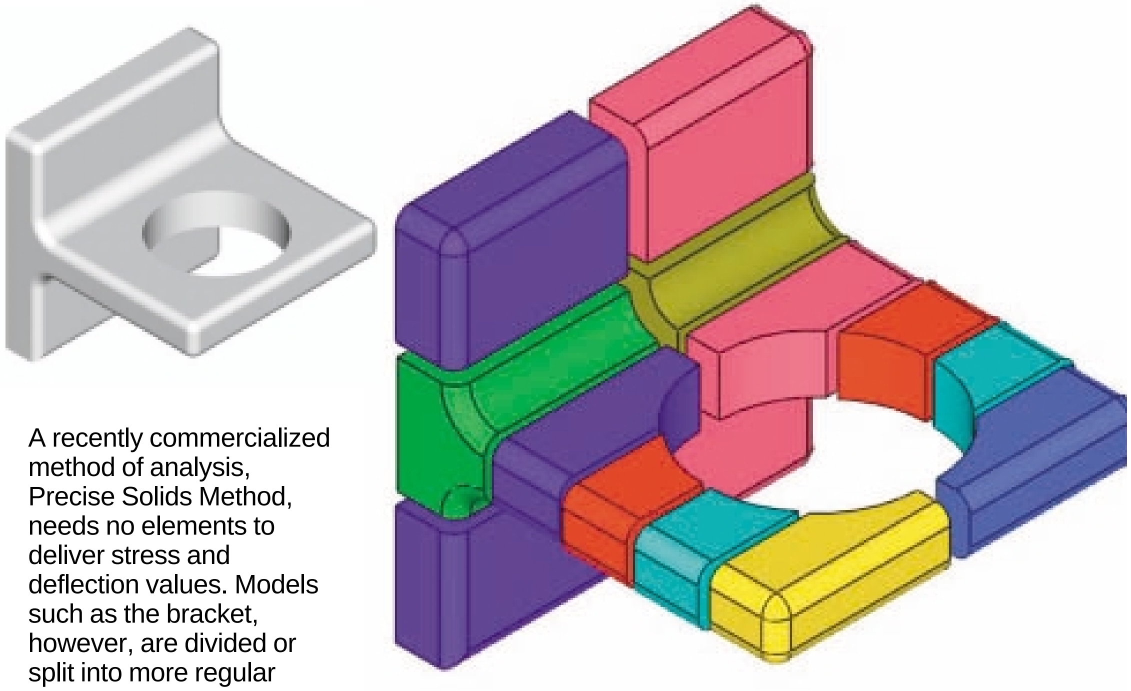
Penton

Penton Media, Inc.

SAY GOOD-BYE TO DEFEATURING AND MESHING

A next generation of design analysis breaks with tradition by working on exact solid CAD geometry and needing no mesh.

Paul Kurowski
President
Design Generator Inc.
London, Ont., Canada



A recently commercialized method of analysis, Precise Solids Method, needs no elements to deliver stress and deflection values. Models such as the bracket, however, are divided or split into more regular subparts before a run.

Procision, the commercial version of PSM, comes from Procision Analysis Inc., Mississauga, Ont., Canada, and is marketed by Rand Worldwide, also of Mississauga.

A proven way to cut costs and time from new-product development is to perform design analyses on parts that are devised. Then, if a problem is found, modifications can be made easily and inexpensively because parts are still in their electronic formats.

The idea is good but several problems pop up when a team of designers, CAD operators, and finite-element analysts try working smoothly together. For one, running a complex FEA program is still the realm of dedicated analysts, not designers. Before using FEA software skillfully and accurately, engineers must climb a long learning curve. And although a CAD model can be transferred easily into an FEA program, the model often must be idealized, defeatured, or simplified to make it suitable for analysis. The task can be time-consuming and ruins the efficiency of working directly with CAD geometry.

The problem lies in small-part details that are essential to CAD models but have little effect on analysis and should be removed to avoid unnecessary complications. If left in place, automatic meshers cram these tiny features with many small and useless elements, producing FE models of ungainly size that take hours or days to solve. Often meshing is not possible at all and geometry must be simplified not just to reduce the solution time but to make it meshable. Consequently, it is necessary to distinguish between CAD-specific and analysis-specific geometry.

This situation is about to change, however, thanks to a recently developed analysis method that promises to improve the relationship between CAD and analysis technologies. The Precise Solids Method (PSM) overcomes limitations in FEA, which must have a mesh as a prerequisite to analysis. For one, PSM works directly on solid CAD geometry regardless of complexity and without idealization, simplification, clean up, or defeaturing. It is based on mathematical methods proposed by Victor Apanovitch and

Comparing the stress-analysis methods

H-ELEMENTS	P-ELEMENTS	PRECISE-SOLID METHOD
Element shapes: tetrahedral, wedge, and hexahedral	Element shapes: tetrahedral, wedge, hexahedral	Subpart shape: Almost anything. There are no restrictions.
Mapping (meshing) allows little deviation from ideal shapes.	Mapping handles greater deviations from ideal shapes but may introduce errors on highly curved edges and surfaces.	No mapping is performed. Deviation from an ideal shape does not apply.
Displacement fields described by lower-order polynomials (first or second order) Polynomial order does not change during solution.	Displacement field is described by mapped higher-order polynomials, up to ninth order. Polynomial order adjusts automatically to meet user's accuracy requirements.	Displacement field is described by higher-order polynomials, up to the 12th order. Stress concentrations are modeled by nonalgebraic functions.

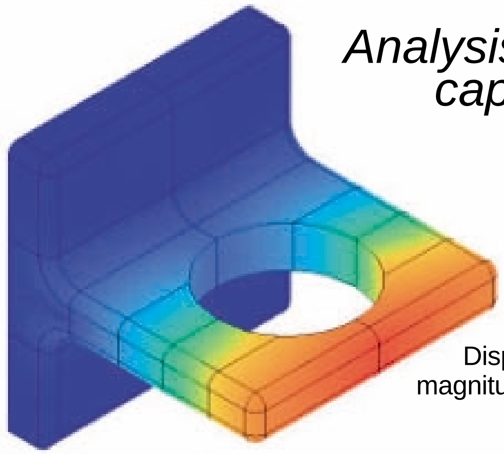
commercialized as Procision software from Procision Analysis Inc., Mississauga, Ontario, Canada.

A LITTLE HISTORY

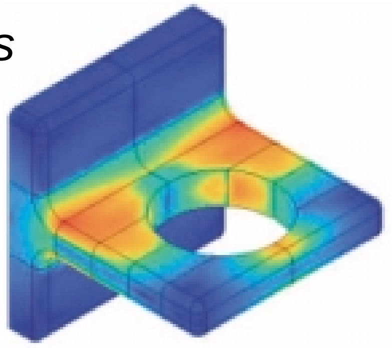
Over the past several decades, designers have migrated from manual to electronic drafting, later to 3D wire-frame models, and more recently to solid modeling. Ever more sophisticated CAD tools and improved manufacturing and tooling methods have spurred designs of increasing complexity.

Companies developing finite-element-

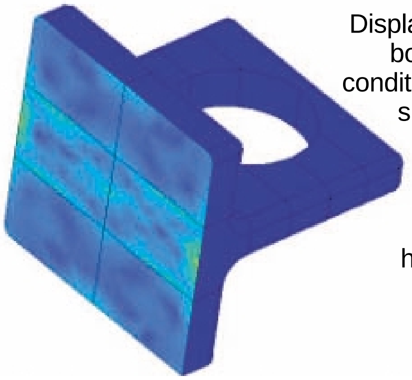
Analysis of a bracket shows capabilities of PSM



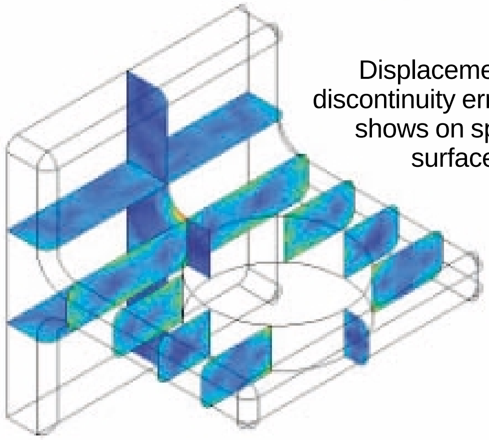
Displacement magnitude results



Von Mises stress results



Displacement boundary-condition error shows on surface where built-in support has been defined.



Displacement discontinuity error shows on split surfaces.

A closer look at different FEA versions

The **h-method** uses elements of simple shapes. Because it is not always possible to mesh geometry with nicely shaped elements and keep their number reasonably low, models often end up with degenerated elements, a huge number of elements, or both. Displacement fields in h-elements are described by simple polynomials (first or second order), so it is easy to miss important displacement and stress gradients by placing too few elements in areas of interest. Low-order displacement fields call for many tiny elements to represent the expected displacement and stress patterns. Even though meshing geometry is most often done automatically, the user determines when the mesh is good enough to deliver needed results. Controlling error requires a tedious process of mesh refinement that is rarely done in practice.

The first commercial h-method programs were well suited for dealing with simple geometry. Analysis was done independently of CAD. There were no user interfaces because there was nothing to interface with. Turnaround time was not much of an issue either.

Using the FEA h-method concurrently with a design process creates several difficulties. For example, users must prepare CAD geometry for analysis, and judge the correctness of mesh, accuracy, and quality of results. This takes a dedicated FEA expert, not a design engineer.

The **p-method** loosened the tight h-method requirements a bit by using more complex elements. This means the p-method does not need as many elements to map a particular geometry. However, mapping may introduce errors. The p-method also allows more deviation from the ideal element shape than is tolerated by the h-method, so an automesher finds it easier to accomplish its task. Displacement fields in p-element technology are described by higher-order polynomials (up to ninth order) allowing for larger elements and relieving users from worries over having enough elements in areas of interest. P-method solutions are iterative so convergence errors are automatically calculated.

Commercial p-methods brought integrated analyses closer to reality about ten years ago. Still, CAD geometry must often be idealized and defeatured for it to work most efficiently. This inhibits complete integration of design and analysis.

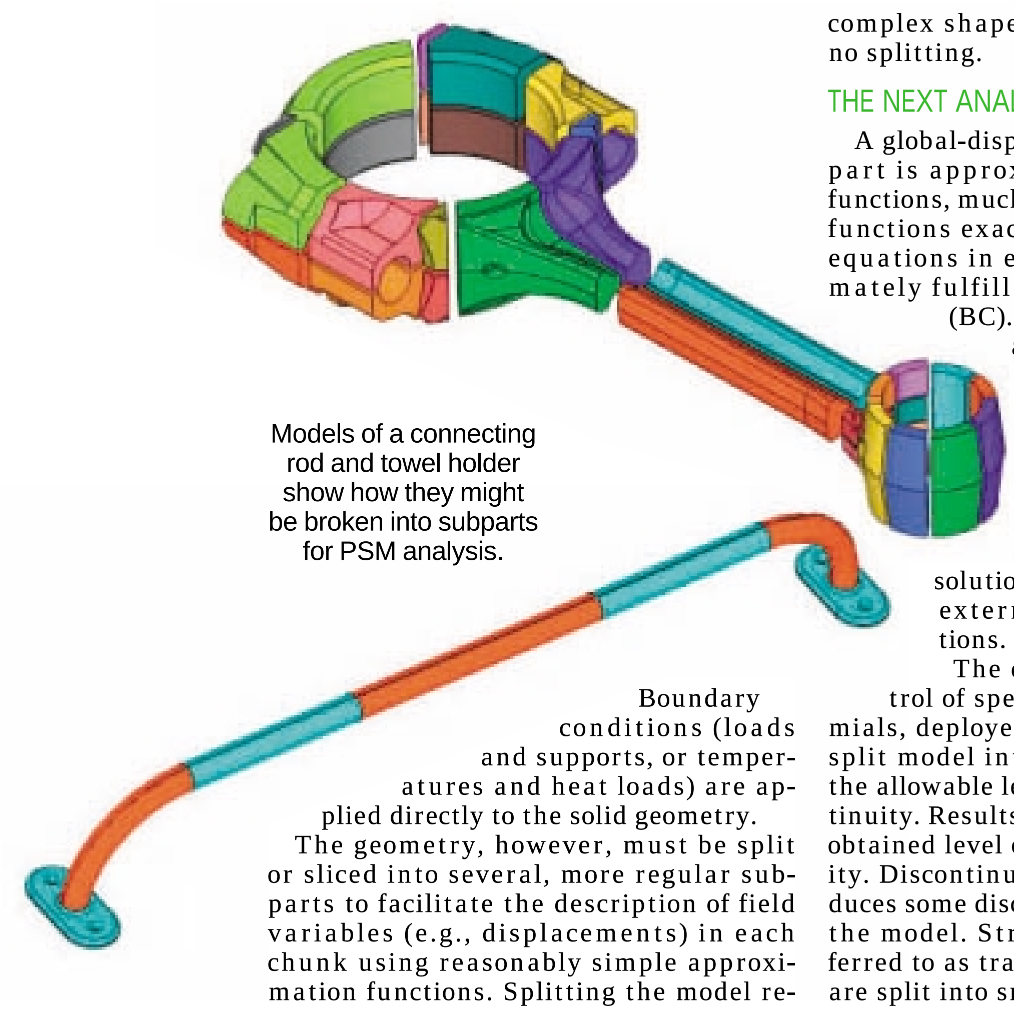
The **Precise Solids Method** (PSM) is based on an external finite-element approximation method. It belongs in the same class of tools as FEA, but strictly speaking is not FEA. As the term “precise solids” indicates, PSM analysis is conducted directly on solid CAD geometry of any complexity. Geometry defeaturing and cleanup is not required. There is no mesh, although the model is divided into subparts of almost any shape.

There is also no need for analysis-specific geometry or interfacing issues because PSM offers complete integration with design. PSM allows for a more complete, concurrent-design process and delivers the time and cost savings of integrated analysis.

based simulation tools tried to keep up with the increasing complexity of geometry. The h-method for FEA, for instance, entered the engineering world in the 1970s. It could handle the simple geometry of early CAD.

The p-method dealt with the more complex designs of the early 1990s, but even this advanced FEA technology has difficulty with truly complex geometry. In addition, it is still subject to limitations of the finite-element method: it needs a mesh to provide results. And meshing requires simplifications, idealizations, and defeaturing, a process that is not easily run by designers and does not fully integrate into the design process.

PSM is similar to but not the same as the finite-element method. This recent technology does not require a mesh and, consequently does not require idealized CAD geometry. There is no 2D analysis either because every problem is treated as a 3D solid, just as in CAD. Since there is no mesh, we have no meshing problems such as degenerated elements, no inability to mesh complicated details, and no difficulties with “dirty” or flawed geometry.



Models of a connecting rod and towel holder show how they might be broken into subparts for PSM analysis.

Boundary conditions (loads and supports, or temperatures and heat loads) are applied directly to the solid geometry.

The geometry, however, must be split or sliced into several, more regular subparts to facilitate the description of field variables (e.g., displacements) in each chunk using reasonably simple approximation functions. Splitting the model reduces the complexity of its formulations because even PSM's advanced mathematics may have trouble dealing with overly complex shapes. Simple geometry needs no splitting.

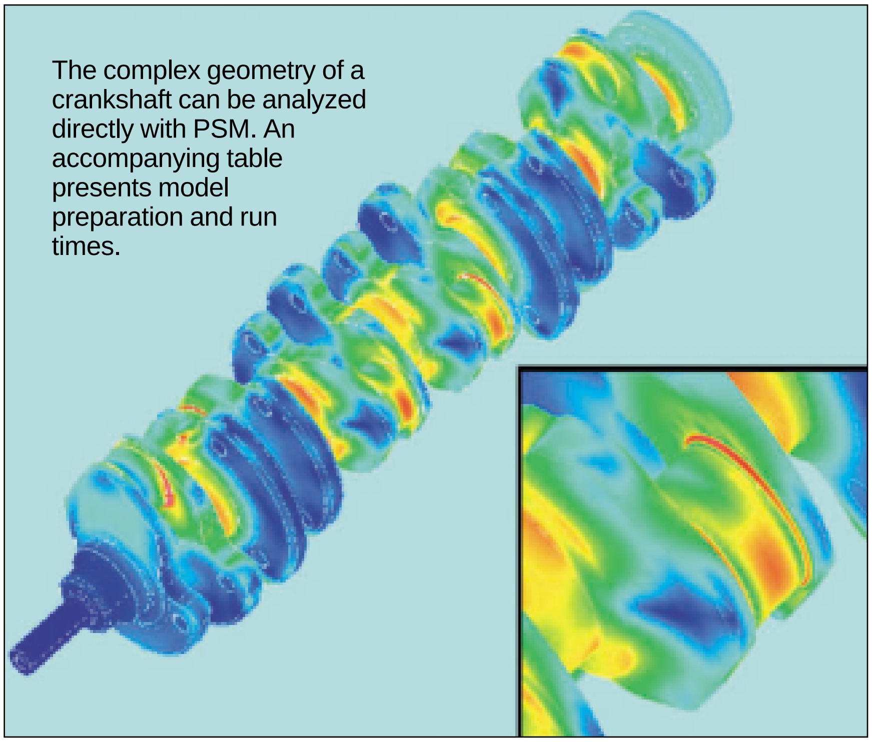
THE NEXT ANALYSIS STEP

A global-displacement field in each subpart is approximated with polynomial functions, much the same as in FEA. These functions exactly fulfill the equilibrium equations in each subpart and approximately fulfill the boundary conditions (BC). For this reason, the PSM is also called the External Finite Element Approximation Method because BCs are only approximately fulfilled and the model's global displacement field is only approximately continuous. Hence, solutions are obtained "outside" or external to classical FEA solutions.

The discontinuity is under control of special functions, also polynomials, deployed along the cuts created to split model into subparts. Users specify the allowable level of displacement discontinuity. Results include information on the obtained level of displacement discontinuity. Discontinuity of displacements introduces some discontinuities of stress flow in the model. Stresses on a surface are referred to as tractions. And because models are split into smaller sections, the amount of traction discontinuity across splitting surfaces is specified by users and reported in results.

Formulating h and p-elements in FEA and subparts in PSM

	FINITE-ELEMENT METHOD	PRECISE-SOLIDS METHOD
APPROXIMATING DISPLACEMENTS FIELD	Polynomial functions approximate both global and local model behavior. These functions cease to be polynomial when mapped on curved geometry.	Volume functions (polynomials) are responsible for modeling approximate global behavior of the subpart. Boundary displacement function (polynomials) approximate displacement and force boundary conditions. They must also satisfy the displacement and force continuity across subpart dividers. Stress concentration functions are nonalgebraic. They model stress concentrations near small details such as holes, notches, grooves, and fillets.
SATISFYING BOUNDARY CONDITIONS	Displacement BC are fully met, force BC are approximately met.	Displacement and force BC are approximately met.
SATISFYING EQUILIBRIUM IN THE VOLUME	Governing equations are only approximately fulfilled in the volume.	Governing equations are fulfilled exactly in the volume, making it possible to assess accuracy in terms of BC error.
STRESS CALCULATIONS	Surface stresses must be extrapolated from integration points in the volume.	Stress are calculated directly on surfaces.



The complex geometry of a crankshaft can be analyzed directly with PSM. An accompanying table presents model preparation and run times.

Time comparisons for the crankshaft

ACTION	H-ELEMENTS (min)	P-ELEMENTS (min)	PRECISE-SOLID METHOD (min)
Defeature	90	60	0
Split into subparts	0	0	25
Mesh	90	120	0
Solve	355	525	40
Total	535	705	65

The table shows times for trained users to prepare and analyze the crankshaft in an accompanying image. All methods calculated Von Mises stresses and were within 3%.

PSM also uses surface tractions to assess the accuracy of solutions. On loaded surfaces, tractions should equal the applied load and on surfaces where supports are defined, tractions should equal the reactions. Finally, tractions should be equal to zero on all free surfaces.

All the above requirements are only approximately fulfilled, but users decide by how much and in this way they determine certain accuracy of the results in terms of absolute BC errors. The BC errors (both displacements and tractions) are called absolute because both actual and target values are known. For example, we know from analysis results what the tractions are on an unloaded surface — they should be zero.

In summary, global-displacement functions are responsible for the global behavior of the model. Other functions control displacement BCs, displacement discontinuity, traction BCs, and traction discontinuity. Everything controlled by the functions are subject to "quality control," and the final accuracy is reported to users.

On top of the global-approximation functions and BC approximation functions, special nonalgebraic functions model stress concentrations around small features such as holes and notches. These nonalgebraic functions are expressed as differential operators and integrals, but they lead to systems of linear algebraic equations just as they do in traditional FE modeling.

Those familiar with traditional FEA will be glad to learn that the Precise Solids Method does not displace older technology. Some structures do not lend themselves to solid modeling, they need the beam and shell techniques the h-method handles well. At present, Procision (the commercial implementation of PSM) complements existing methods and let designers analyze complex geometry in short time. Procision runs inside Pro/Engineer, offering full integration of design with analysis. It is also well suited for the Internet Age. The entire code can be compressed to 3 Mbytes and is easy to distribute over the Web.

Procision shows its powers working with large, complex 3D solid models that would ordinarily require lots of simplification work to make them ready for traditional FEA methods. And although this discussion dealt primarily with structural analysis, PSM theoretically can simulate any kind of phenomena that is described with differential equations as boundary-value problems.

Perhaps the most promising development in the new technology is that by working directly on CAD models and using a familiar CAD interface, software is finally being tailored for the integrated

We want your feedback.

Did you find this material interesting?	Circle 841
Do you want more information of this type?	Circle 842

Comment via e-mail to mdeditor@penton.com

What related topics would you like to see covered? What additional information on this topic would you find useful?