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Testing vs Finite Element analysis What should the balance be?

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Abstract

To assist in the licensing of nuclear transport packages the use of Finite Element Analysis (FEA) and indeed many other forms of simulation has increased dramatically over the past years. The amount of physical testing has similarly reduced. With more and more FEA and less and less physical testing taking place, where is the correct balance that provides sufficient confidence to the regulatory bodies and where should the focus be?

FEA is now capable of providing very precise results in the hands of suitably qualified and experienced people, however the accuracy can only be determined by comparison with physical test results. Should the testing be limited to component testing where there are fewer unknowns and fewer variables, such as simulating tensile tests or simple crush tests or should testing only take place on the final package?

This paper presents both ends of the arguments indicating the pit falls and benefits of both extremes and seeks to find a happy medium without significant safety or cost implications.

The start of Finite Element Analysis (FEA)

It is probably worth initially describing what FEA actually is. In simple terms it is a process of breaking down a complex problem in to a large number of very simple problems. These simple problems have a known solution and these solutions are recombined to provide a final solution for the complex problem.

The history of FEA is difficult to determine. Wikipedia [1] contains various dates and names but in practice the roots of FEA exist in the requirement to solve simultaneous and partial differential equations.

Numerous mathematicians and engineers worked in parallel to find better ways to solve the problems that were presented to them and in the 1950s and 1960s these solutions started to take shape and be shared.

In the 1960s and 1970s the universities started to get interested and the Finite Element Method gained impetus with larger government bodies, such as NASA [2], starting to get interested too.

In the early 1980s the theory was well developed and the methods established.

A brief history of FEA developments

In the mid 1980s the main analysis codes provided 2 dimensional analysis only, such as Principia Mechanica's PR2D [3] and Lawrence Livermore National Laboratory's DYNA2D [4] impact codes. These provided the capability to create and analyse FEA models for dynamic analysis which typically consisted of up to 500 finite elements using either plane stress/strain or axisymmetric. Other analysis codes were available which provided thermal analysis (TOPAZ [5]) and structural analysis (ANSYS [6]) amongst many others.
At this stage the use of computers in industry was still very limited and the provision of graphics was almost non-existent. A large amount of the mesh development was done off-line. The nodal coordinates were calculated by hand based on hand drawn sketches of the proposed FE mesh.
In general the type of analyses that could be assessed were limited by the 2D nature of the model. In the case of nuclear transport packages, impacts on to the lid and the base were the only sensible assessments that could be done and some careful adjustment of the material properties of non-axisymmetric components, such as lid bolts, had to be made to give representative values.

The late 1980s hailed the arrival of 3 dimensional analysis codes, such as DYNA3D [7], along with the exponential increase in computing power and introduction of reliable and cheaper graphics. It was now becoming possible to visualise the FE mesh on the screen before submitting it for analysis and the possibilities of FEA increased significantly. From an impact point of view it was now possible to look at a number of different orientations to determine which ones would be the most challenging for drop testing. With the increased usage of 3D modelling the size of the FE models started to increase with many models containing up to 2000 elements.

As the compute power increased so did the complexity and ingenuity of the analysts. In the early 1990s BNFL [8] created a wood material option based on some preliminary testing completed at the University of Manchester [9]. LS-DYNA [10] started to really develop as the front runner for impact analysis with many more material options, including many non-metallic materials such as wood, plastic, foam, being introduced.
It was around this time that the regulators started to get very interested in the capability and expected to see a considerable amount of FE to support the safety cases. They also started to get their own in-house experts. This put a greater demand on the FE analysts as the regulators started to "push" for more detailed information to underpin the safety case. Whereas before the focus would have been on predicting strain in the lid bolts it now became possible to start looking at the lid seal gaps and the action of the seal itself. It also became possible to look at the interaction of the contents e.g. how the fuel pins interact with each other and with the internal furniture thereby providing more information to the criticality case.

Throughout the late 1990s and continuing until now, the increase in compute power means that detail in FE models can also increase. The software developers and analysts now look for methods to provide true multi-physics solutions to problems, combining thermal and structural, structural and fluid, etc. It is now possible to start looking at, not only how the fuel interacts with the flask furniture but also how the presence of water in the flask affects the behaviour. Finite element models containing 10s of millions of elements are possible and can be solved overnight.

A brief history of drop testing.

In the early to mid 1980s drop testing was used as a design tool as well as a proving tool. The best method to test out a new design concept was by physical testing. Scale models could be constructed at eighth scale, quarter scale, third scale, etc. depending upon the requirements. It would not be unusual for a number of eighth scale variations of a flask concept to be built and tested to determine which performed the best, to get approximate deformations and accelerations which could then be passed back to the design team to assist in the their calculations.

Post test inspection and measurements were used to guide the designer in ways to improve the design but to determine what had happened in multiple layer packages, e.g. to determine the extent of lead slumping, it would be necessary to section the package.

The usefulness of this was limited to the monolithic type of packages. Thin walled packages were, and still are, harder to scale.

As the capability of FEA increased it became possible to replace the initial small scale models used for concept testing with analysis. The focus for drop testing then moved on to proving the final design with sufficient drop tests to cover a range of orientations.

A series of drop tests performed in the early 2000's still consisted of 17 cumulative drops from various heights on a single package which ultimately resulted in a failure of the containment. This is clearly a very expensive exercise. Subsequent FEA revealed that this was due to the cumulative effects of the five 9m drop tests to which the single package had been subjected.

The cost of manufacturing, testing and potentially retesting has been increasing and the push has been to reduce the number of drop tests and to ensure that they result in success. The increase in capability of FEA has assisted in this and the number of drop tests performed has reduced over the recent years as acceptance of the results from FEA has increased.

What is possible today?

The increased use of FEA has resulted in the number of drop test being reduced. A recent package that had detailed FEA completed underwent only two drop test series and subsequently resulted in a transport license being issued. The FEA consisted of preliminary design assessment on simplified FE models to provide confidence that the overall performance of the package and selection of materials could provide a solution that would meet the transport requirements. This simplified model, with a few improvements based on the initial results, was then used to provide information to assist in defining the worst orientations for impact testing. By running analyses for a large number of orientations, in this case a cuboid shaped package resulting in over 100 different orientations, the comparative results of strains, accelerations, deformations and forces can be studied to determine which orientations will challenge the containment, criticality, contents retention, etc. A fully detailed FE model was then created to provide results for a significantly smaller number of orientations and this was used to drive the decision on the final two orientations selected for drop testing. The results from the drop testing and detailed FEA compared very well.

It is worth noting that the package described above was a dry package with fully described contents that could be, and were, modelled in detail. The fuel elements were modelled in such detail that individual fuel pellets were included within the fuel pins of each element. The material data used for each component in the FEA were taken from material tests and from British standards at various temperatures to provide a range of values. Details of welds were explicitly included in the FE model allowing failure of the welds to be predicted. All these details ensured that the drop test results and FE results agreed well.

What does the future hold?

It is clear from the above that it is possible to predict the results from drop testing, of a dry package, given suitable information on materials, weld details and geometry. It is also possible to simulate the behavior of fluid within packages, to simulate the variation of material properties with temperature, to simulate fluid flow around the outside of packages and much more. This begs the question;
Is it possible to complete sufficient FEA such that drop testing is no longer required?
This question can also be phrased the other way.
If drop testing is not performed how much FEA is required to support it?

In either case it is not always possible to perform a drop test of the exact items to be transported. Testing of actual fuel or waste in a transport package is not an acceptable risk so some assumptions or predictions will always have to be made. Therefore given that a drop test will always be an approximation, why would it not be possible to use FEA as the approximation? Consider the following:

- A monolithic cylindrical finned flask
- Solid lid secured by M52 bolts torqued to a known value
- Sealed with typical O ring seals
- Wood and metal overpack external shock absorbers attached by M30 bolts torqued to a known value

- Internal thin steel welded basket containing new fuel at a known heat load

All of the items above can be fully described in terms of dimensions, material properties, temperatures, pre-stress, etc. Even the fuel pellets properties are well understood and defined. With the power of today's computers it is possible to construct a detailed FE model with sufficient detail to predict weld failure, thermal expansion, bolt pre-loads, etc. Unknown variables, such as coefficient of friction, can be varied with a FE model to determine the effects. Variations in thickness of thin sheets can be studied in the FEA. Varied positions of the fuel and basket can be studied in the FEA. Seal recovery during and after impact can be predicted in the FEA. Internal pressure can be adjusted during impact in the FEA. In general given sufficient time it is possible to study variations in any items and provide a range of predictions, so why bother with drop testing?

Conversely, a full scale model of a flask can include all the details, including accurate representations of the fuel or other contents. It will be constructed using the same techniques and equipment as the production flask and in doing so may identify issues with welding techniques. Warpage due to welding and heat affected zones may be generated, something that is possible to model in FEA but very difficult to predict.

A full scale prototype model of a large monolithic flask is an expensive item to produce, especially if the intention is to only produce a very small number for use, but they can be scaled reasonably easily. If the intention is to produce a large number of the flasks, 100s in the case of smaller thin walled drum like flasks, then the production of a few more for testing is a smaller percentage of the total cost. Given the ability to scale down larger monolithic flasks to reduce the cost and the relatively low cost of producing a few more thin walled flasks from a large production run it would seem reasonable to perform a limited number of drop tests based on the findings from FEA.

A third route to licensing exists which relies on existing physical tests. If a sufficiently similar flask has already been tested, it should be possible to provide evidence that the new, or modified, flask will perform in an almost identical way. Using FEA to replicate the original results from the drop testing and then modifying the FE model to represent the new flask could potentially remove the need for additional drop testing. This approach, however, requires an understanding of what "sufficiently similar" means. It is interesting to note that at present NAFEMS [11], the International Association for the Engineering Modelling, Analysis and Simulation Community, are addressing what is meant by Validation in order to satisfy the requirements of ISO 9001 [12]. Although the process flow chart has not yet been completed it will indicate two routes to validation. The first is using Predictive Capability Assessment (PCA), which includes FEA as well as other methods, that is directly supported by physical tests. The second route is using PCA that is indirectly supported by physical tests. The debate on whether there is a third route that uses PCA not supported by physical tests continues within the NAFEMS Analysis Management Working Group (AMWG).

Conclusions

FEA is clearly an invaluable tool and the use of FEA will continue to increase.
The use of FEA can assist in reducing costs of manufacturing and can support and possibly, given sufficient related physical testing, replace the requirement for drop testing in certain cases.
There is a lot of work being undertaken by NAFEMS AMWG to determine how to validate FEA and crucially if there is a route to allow validation without physical testing.
In answer to the original question, “What should the balance be?”, there is no definitive answer. The use of FEA will increase, the reliability and confidence in FEA will increase, the requirement for drop testing will decrease but every case is unique and the demands are different.

References

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