Use of *INTERFACE_SPRINGBACK to Precondition Beams for Impact Analyses

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1 Abstract

The *INTERFACE_SPRINGBACK card allows LS-DYNA to conveniently export deformed geometry, member stresses and effective plastic strains from one analysis run to another. This facilitates the use of inexpensive implicit analyses to precondition a structure with loads prior to an explicit analysis of a collision or other event of interest.

This paper investigates the usage of the *INTERFACE_SPRINGBACK card as applicable to beam elements. Reasonable agreement is found between implicit-explicit and purely explicit runs, with the former being significantly less computationally demanding.

One limitation of the hybrid process is that the *INTERFACE_SPRINGBACK_DYNA card produces a DYNAIN file with stresses and strains to only 10-bit precision, whilst deformed node locations are given to 16-bit precision. In both cases, 6 bits are reserved for scientific notation of sign and magnitude. The effects of this limited dynamic range can be clearly observed during the equilibrium state from the start of the implicit-explicit runs prior to changes in loading.

In many collision scenarios, where the impact contains much more force than the structure is intended to carry in service, the small numerical errors observed due to limited input and output precision should be within acceptable tolerances.

Despite all of LS-DYNA's native inputs and outputs being of relatively low precision, switching the solvers from (32-bit) single precision to (64-bit) double precision has a measurable positive effect on response calculations, especially for complex structures or long analysis periods.

2 Introduction

When considering a dynamic even, such as an impact, various factors usually mandate that explicit simulations are undertaken of the shortest durations possible, yet often both service and impact loads must be considered. This can be done either by directly including the service loads or directly modelling the deformed geometry of the structure. In the latter case, internal stresses and strains must also be considered.

The convenient approach, then, is to include all applicable loads and allow the structure to find equilibrium positions before the impact occurs. However, for large complex structures, eg the structure illustrated in Fig. 1, doing this explicitly has decidedly non-trivial time and computational resource requirements.

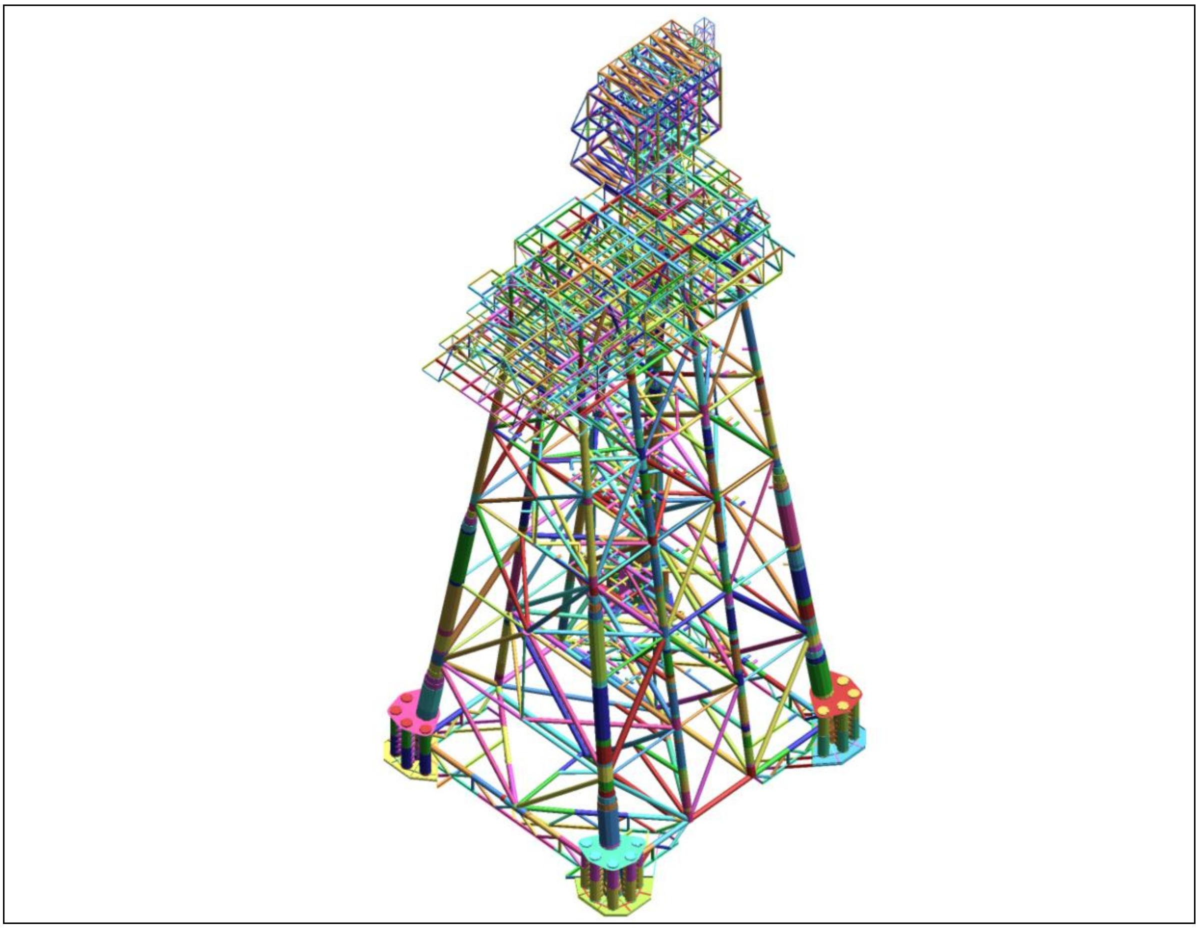

Fig. 1: A complex offshore structure

Fortunately, most service loads can be dealt with by inexpensive implicit analyses.

Exporting the results of implicit runs for use in further analyses is not a new trick, but LS-DYNA has some exceptional support for this approach in the form of the *INTERFACE_SPRINGBACK series of cards [1].

The purpose of this short paper is to investigate the usage of the *INTERFACE_SPRINGBACK cards with some simple beam models and build confidence in the springback (implicit → explicit) approach.

3 Problem Definition

A number of simple beam arrangements subjected to time-varying loads have been investigated. No consideration was given to additional forces or actual impacts as the behaviour of beams in springback analyses has been the focus of this study.

3.1 Run Breakdown

Each analysis run considered three sets of boundary conditions for each of four different possible integration rules, for a total of 12 beams. Fig. 2 illustrates the members considered in a single run.

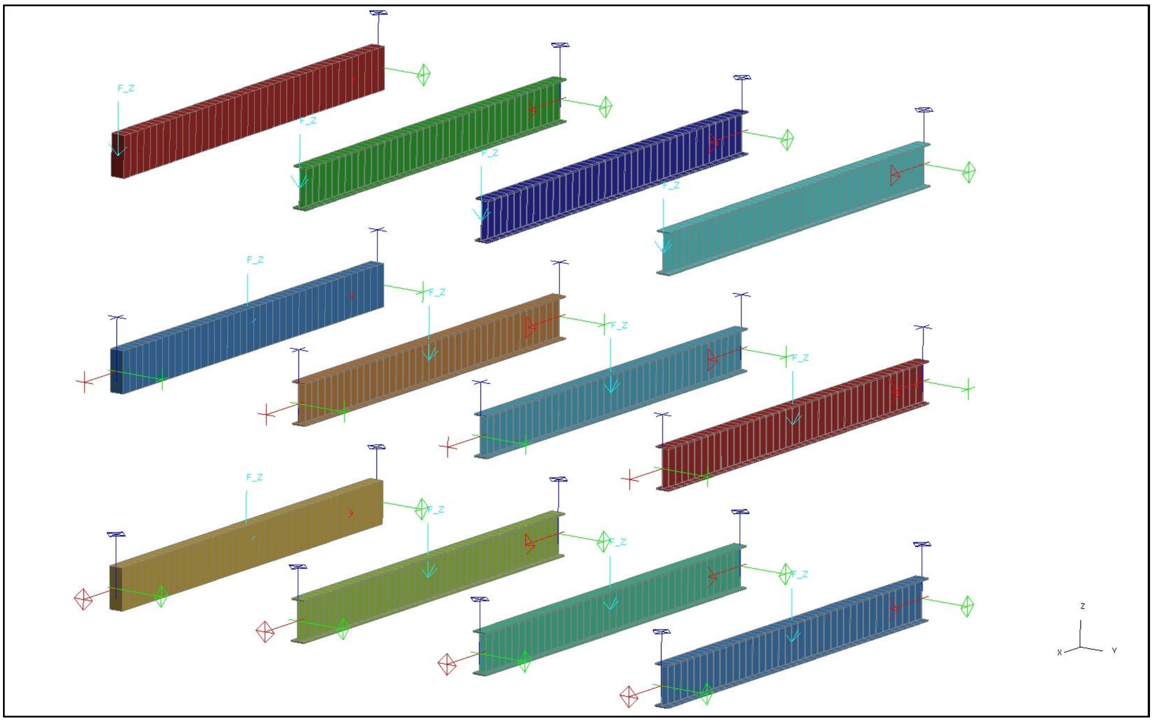

Fig. 2: Analysed beam arrangements

Two batches of runs were undertaken. One batch was run with the solver set to single precision and the second at double precision. For such simple models, single precision can usually be expected to perform adequately. The use of single precision solvers is commonly a result of trying to achieve moderate savings of time and computational effort at the expense of some accuracy.

Each batch involved the following runs:

- Implicit only
- Explicit only
  - Undamped
  - 0.5% damping
  - 5.0% damping
- Explicit utilising earlier implicit results (springback)
  - Undamped
  - 0.5% damping
  - 5.0% damping

3.2 Boundary Conditions

All beams were simple I-sections with the following geometries:

Depth:	1,000 mm
Width:	350 mm
Web thickness:	20 mm
Flange thickness:	35 mm
Length:	10,000 mm

3.2.1 Arrangement 1: Cantilever

Clamped at one end, forces applied at free end (10 m).

3.2.2 Arrangement 2: Simply supported

Knife-edge supports at each end, forces applied mid-span (5 m), torsional rotational restraint at one end.

3.2.3 Arrangement 3: Two fixed ends

Clamped at each end, forces applied mid-span (5 m).

3.3 Section Properties

Hughes-Liu beams with cross section integration were used. The following integration rules were applied:

- A custom integration rule representing the I-section considered, with 15 integration points
- Standard catalogue cross-section type 1, I-section, 15 integration points
- Standard catalogue cross-section type 10, I-section, 15 integration points
- Standard catalogue cross-section type 15, I-section with a web two integration points thick, 22 integration points in total

As outlined in Fig. 3, integration rules type 1 and 10 were effectively identical and thus only integration rule type 1 was considered when extracting results. Theoretically the custom integration rule used was also identical to type 1, but suffered from reduced numerical input precision and thus small discrepancies existed.

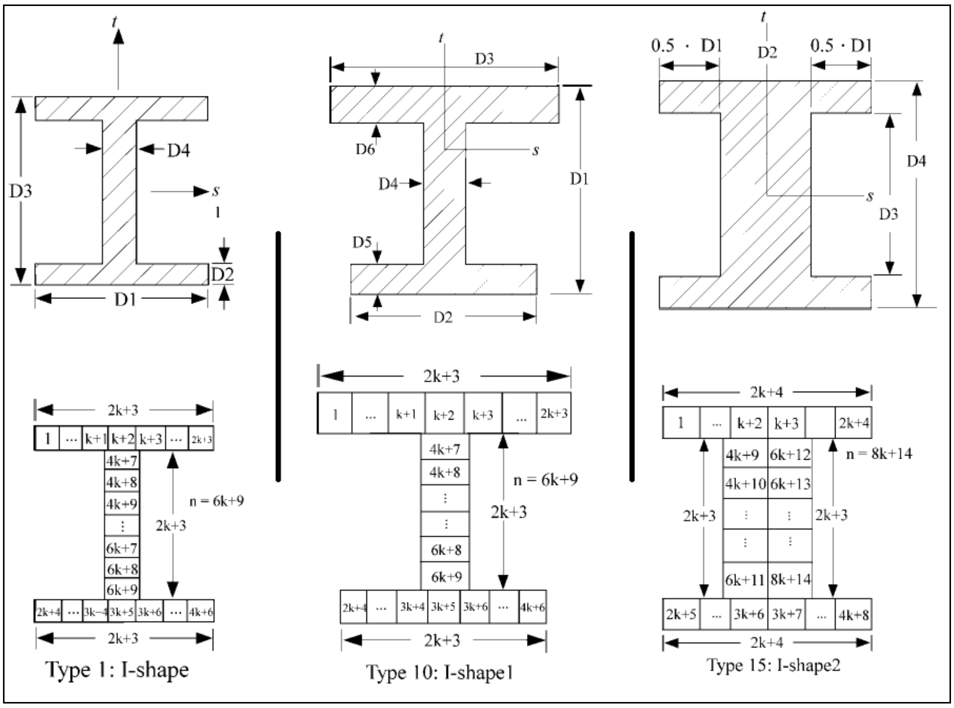

Fig. 3: Catalogue [1] integrations rules type 1, 10 and 15

3.4 Materials

The material properties for steel in grade S420, including the stress-strain curve defined in Table 1, were applied.

Material type:	MAT_024: Piecewise_linear_plasticity
Young's modulus:	2.0e+05 N/mm^2
Density:	7.8e-09 T/mm^3
Yield stress:	420 N/mm^2
Failure strain:	0.15

Table 1: Stress-strain curve for S420 steel

Strain	0	0.006	0.015	0.022	0.031	0.043	0.059	0.258
Stress [N/mm^2]	420	440	460	480	500	520	540	640

3.5 Load Functions

A load function was specified using a series of four second ‘steps’ to facilitate easy checking with hand calculations and readily illustrate the effects of damping and other key factors. Fig. 4 illustrates the applied force history.

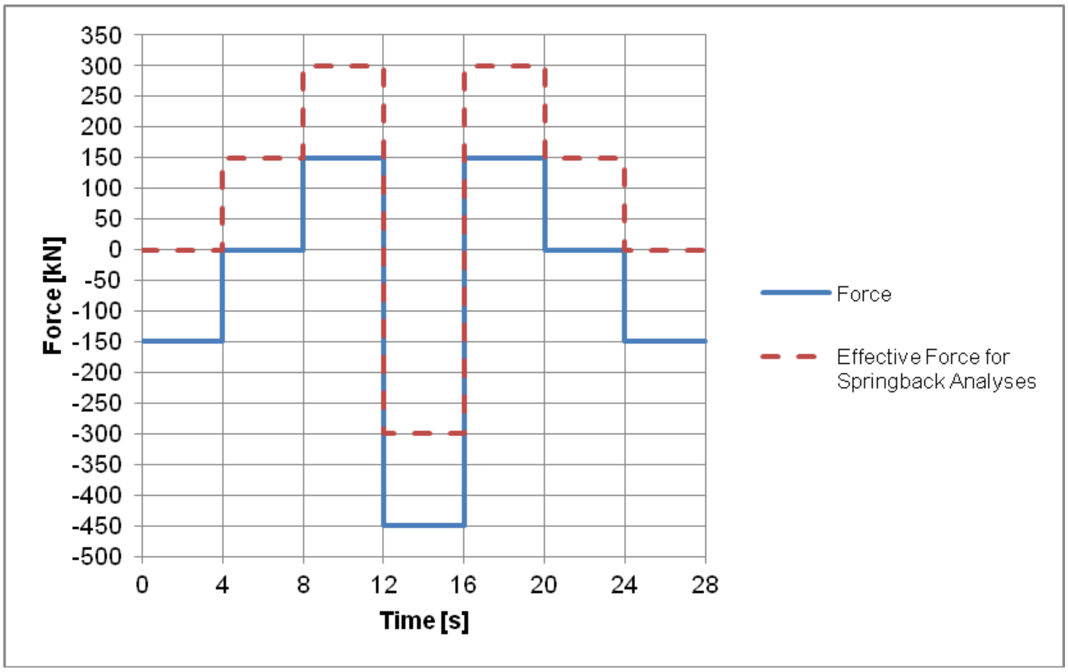

Fig. 4: Applied and effective (as exerted in the explicit part of the springback run) force time histories

There are some considerations in the selection of a forcing function for springback analyses:

Firstly, an implicit analysis finds equilibrium for each ‘loadstep’ independently. Thus, with the force history in Fig. 4, no residual plastic strains from exceeding the 296 kN elastic capacity of the cantilever would be carried into the explicit part of a springback analysis as the final load applied was considerably below this level.

However, by ensuring that the first loadstep of the implicit stage of the springback analysis has the same load as the end of the implicit analysis, zero deflections can be expected in the first few seconds of the explicit run. This happens as the DYNAIN file exported at the end of the implicit analysis and used to start the explicit analysis should have the beam geometry and stresses already set to the equilibrium position for those specified loads.

This means that the effective forces in the springback runs were 150 kN lower and made direct comparisons with the purely explicit runs, which used the unmodified forcing function, difficult.

3.6 Damping

The *DAMPING_FREQUENCY_RANGE card was used with an interval of 5.0 – 50.0 Hz.

However, the fundamental frequencies of the beams are approximately 23.5 Hz, 66.1 Hz and 156.5 Hz for the cantilever, simply supported and two fixed end arrangements, respectively. A different interval (20-200 Hz) would have been more appropriate, but was not necessary for comparing like-with-like results without an equivalent real-world problem.

4 Discussion

Where appropriate, responses were taken from beneath the applied forces, at the free end or mid-span, respectively.

4.1 Development of DYNAIN Files

At the end of a run containing the *INTERFACE_SPRINGBACK card, LS-DYNA produces a file containing deformed geometries and residual stresses and strains. Different suffixes to the card allow different output formats to be created, so eg the _DYNA suffix creates a file named DYNAIN containing LS-DYNA cards and keywords for nodes, elements and initial stresses. This file sets up the next phase of analysis nicely, and can be used with the *INCLUDE command.

However, the RULE flag on the *INITIAL_STRESS_BEAM card defaults to –PartNumber. This confuses LS-DYNA and raises checking errors in Oasys PRIMER [2]. The Keyword Manual [1] suggests that the RULE flag should actually depend upon the type of integration rule used by the beam, with a value of between one and five.

To test the robustness of this card, multiple runs tried setting the RULE flag to +1 (based upon the Keyword Manual entry [1]) and +PartNumber. However, the runs all gave the same results.

It was fortunately possible to automate the modifications of the DYNAIN files produced by the *INTERFACE_SPRINGBACK_DYNA card by using shell scripts calling a stream editor to find and replace certain arrangements of characters.

As with all flat files produced or read by LS-DYNA, the fields in the DYNAIN files are of fixed width and have precisions significantly lower than those used internally by the software. This is made visually obvious when comparing the final timestep of the implicit analysis and the first timestep of the subsequent explicit analysis, eg Figs. 5 and 6.

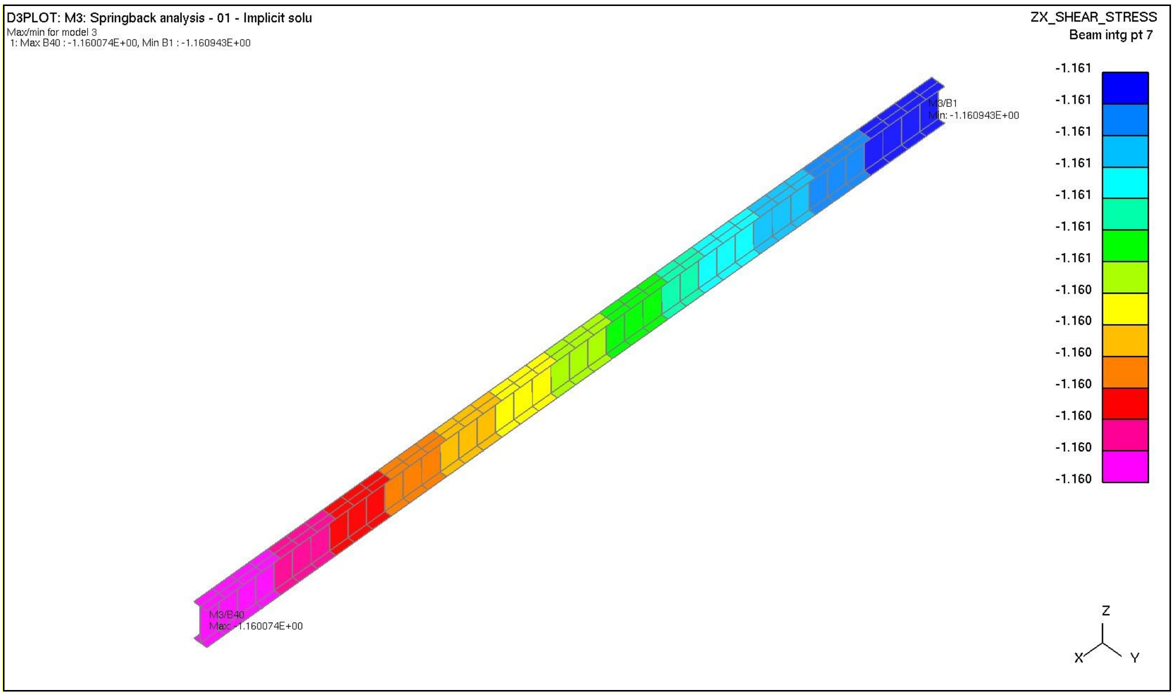

Fig. 5: Shear stress at end of an implicit run

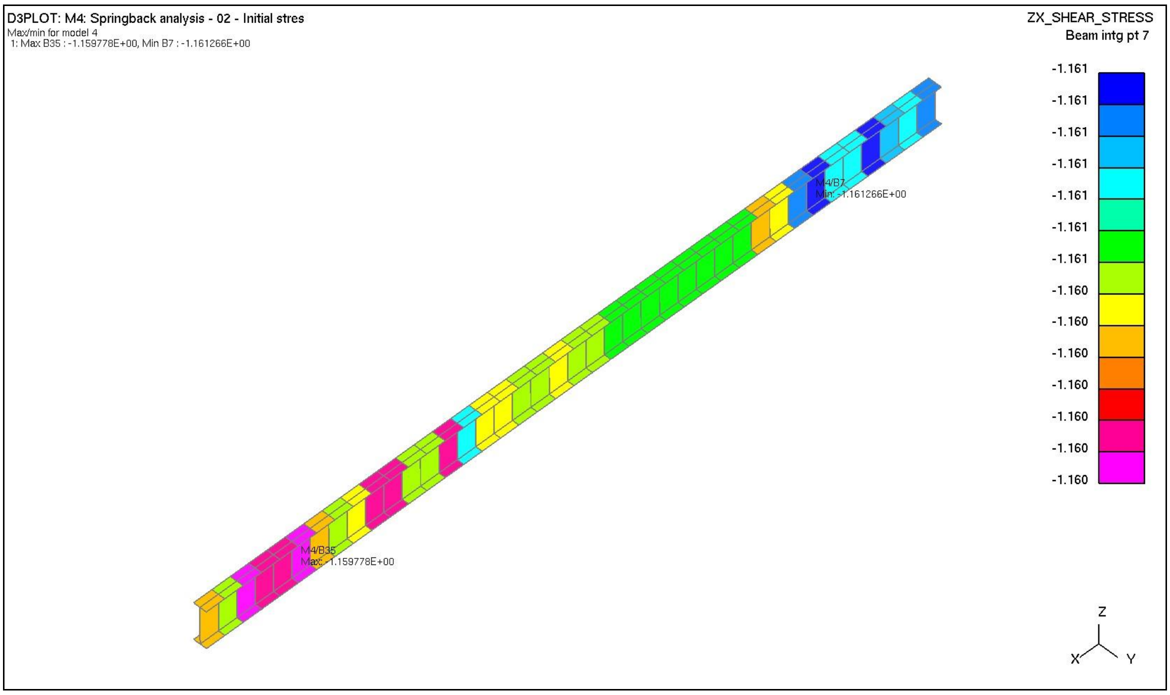

*Fig. 6: Shear stress at start of a subsequent explicit run using *INITIAL_STRESS_BEAM cards, where all conditions should be the same. Numerical errors are small, but visually apparent in software.*

To be more specific, the *INTERFACE_SPRINGBACK_DYNA card produces a file with stresses and strains to only 10-bit precision, whilst deformed node locations are given to 16-bit precision. In both cases, 6 bits are reserved for scientific notation of sign and magnitude. The effects of this limited dynamic range can be clearly observed during the equilibrium state from the start of the implicit-explicit runs prior to changes in loading, eg Fig. 7 where zero deflection would be expected until the first change in applied loading at t = 4 seconds.

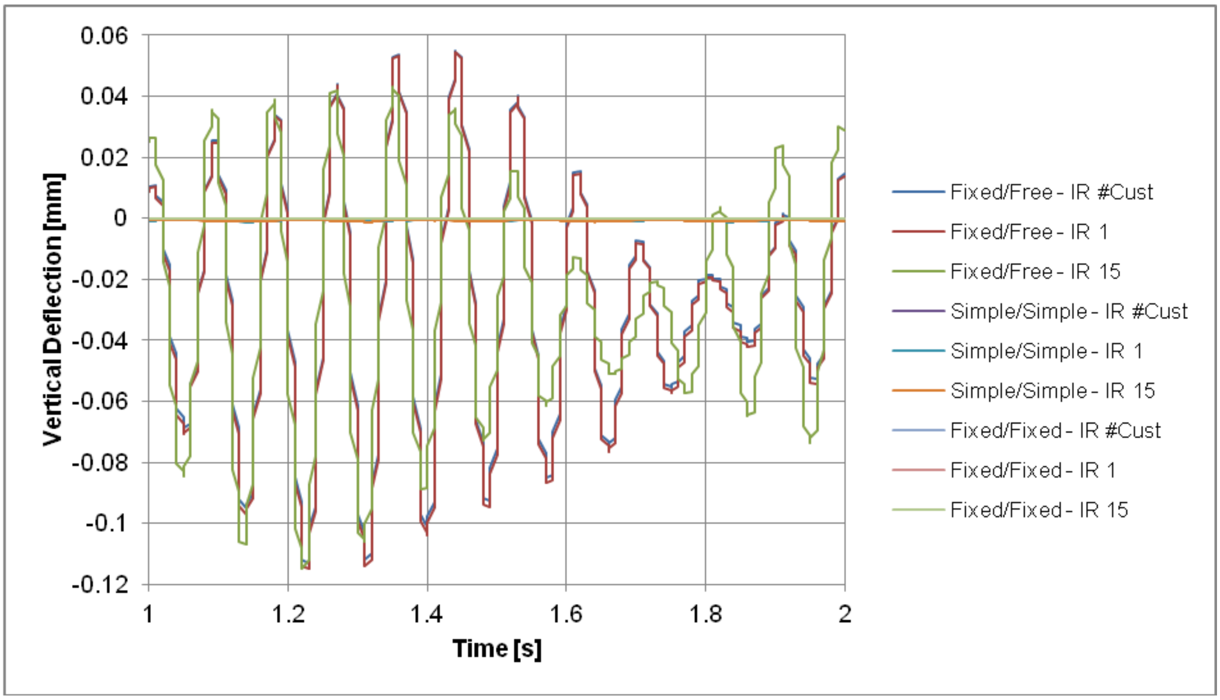

Fig. 7: Example 'errors' induced by limited dynamic range

Whilst LARGE and BINARY flags can be set for output files, neither appear have any effect on the precision of values in the resultant files. 'Seamless' springback analysis is also an option, but ignores contact elements for the implicit parts of the analysis.

4.2 Comparison of Solver Precision

Setting the LS-DYNA solver to single precision can significantly reduce runtimes at the cost of accuracy. For some simple models, or where the analysis duration is very short, this can sometimes be an acceptable trade. However, even the user manual [1] strongly recommends the use of double precision wherever practical.

Table 2 compares the maximum percentage errors between single and double precision (with respect to the double precision solution) for each batch of runs.

Table 2: Maximum resultant error between single and double precision solvers

	Z Deflection	*Overall Deflection Magnitude*	*Internal Energy*
Implicit Only	*0.38 %*	*0.35 %*	*0.28 %*
Explicit, Undamped	*6.69 %*	*0.01 %*	*0.01 %*
Explicit, 0.5% Damping	*4.90 %*	*0.01 %*	*0.03 %*
Explicit, 5% Damping	*4.84 %*	*0.13 %*	*0.28 %*
Implicit → Explicit, Undamped	*14.57 %*	*0.04 %*	*0.01 %*
Implicit → Explicit, 0.5% Damping	*4.97 %*	*0.07 %*	*0.14 %*
Implicit → Explicit, 5% Damping	*1.24 %*	*0.18 %*	*0.24 %*

Even for models as simple as a damped cantilever under quasi-static stepped loading, entering the plastic strain region causes non-trivial errors to arise. In this particular case the errors were at least recoverable - the resulting values did not arise as part of a monotonic response increase and the response histories did not display any unexpected behaviours.

The double precision solver has greater numerical stability. For long-duration, small timestep analyses of complex structures there can be an accumulation of small errors which can make results unreliable and obviously incorrect after a time. Use of greater solver precision reduces these errors and allows longer runs with more complex structures to be completed with relative accuracy.

4.3 Comparison of RULE Flags on *INITIAL_STRESS_BEAM

It is worth mentioning that the files produced by *INTERFACE_SPRINGBACK_DYNA do require some modifications to be made to the RULE flag on their *INITIAL_STRESS_BEAM cards to satisfy the checking criteria of LS-DYNA and Oasys PRIMER [2].

The use of different values for the rule flag (+1; +PartNumber – between 1 and 32 depending upon the beam in consideration) gave identical results to significant precision. The default value (-PartNumber) raised warnings and prevented analyses from running. The Keyword Manual [1] implies that a value between one and five is necessary, as the flag is meant to define the type of integration rule used in the beam formulations.

4.4 Comparison between Purely Explicit and Springback Analyses

The loadstep t = 8.0 – 12.0 for the purely explicit runs had the same effective load magnitude as t = 4.0 – 8.0 seconds for the springback runs using initial stress cards. Whilst there were several other steps which had similar relations, these particular loadsteps followed on from periods of zero applied force and thus contain fewer residual transient components from earlier timesteps, making them most appropriate for like-with-like comparisons.

For the z-only deflections, the discrepancy between the solely explicit and springback analyses (under 0.5% damping) was less than 0.15%. For overall deflection magnitudes the discrepancy was still less than 0.3%. For internal energies the discrepancies were much larger, in the region of 6 – 30%. These values can be accounted for somewhat by the initial 'deformation' and stresses of the springback run, which contribute almost nothing towards the internal energies developed. Figs. 8 and 9 illustrate this behaviour.

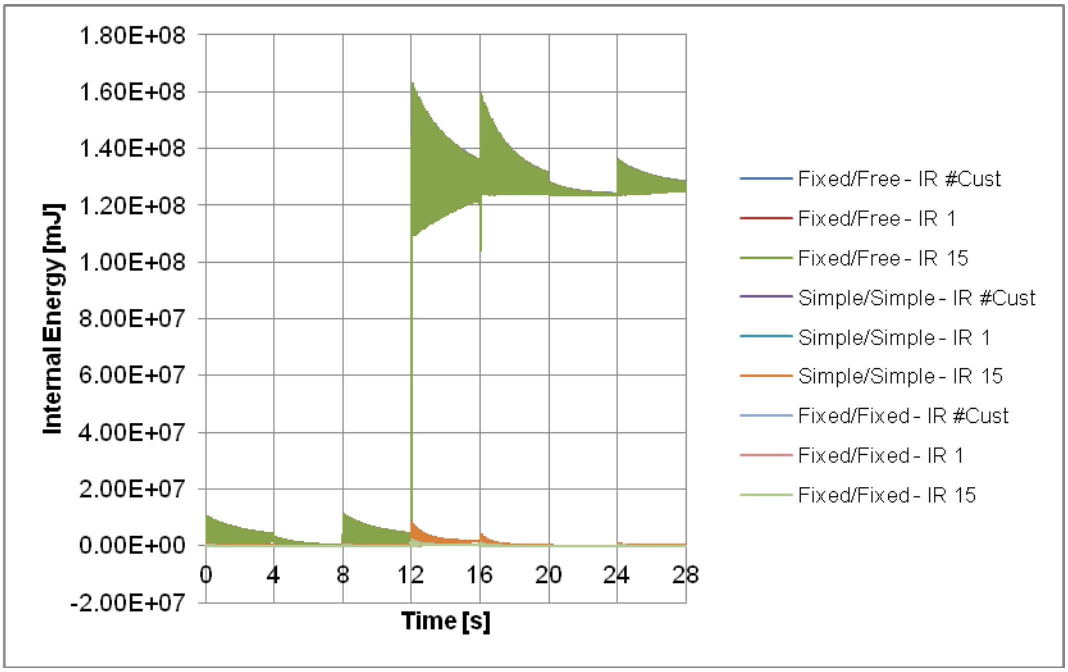

Fig. 8: Internal energies for a wholly explicit run with 0.5% damping under double precision.

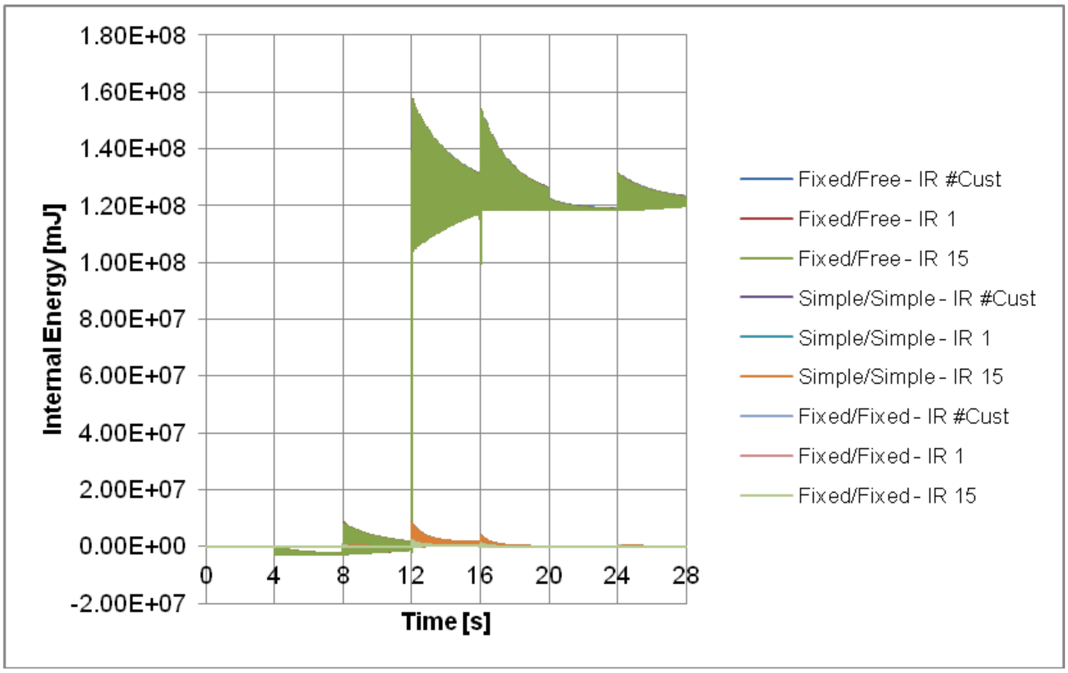

Fig. 9: Internal energies for the explicit phase of a springback run with 0.5% damping under double precision.

5 Summary

Use of the *INTERFACE_SPRINGBACK card allows analyses to switch between implicit and explicit solvers quickly and easily. This enables easy and fast consideration of pre- and post- dynamic event static loads.

Several simple beam arrangements have been considered and results from different analysis techniques have been compared.

The effects of solver precision were investigated. Even for the simple beam models presented herein, non-trivial discrepancies were observed in some of the results. The usage of double precision, as recommended in the LS-DYNA user manuals [1], is thus considered vital.

Good agreement was found between purely explicit and springback analyses. In general, the error between the two approaches was very small (<0.3%), except for the calculation of internal energies. However, those differences arise due to the way internal energies are calculated: the initial deformations and stresses of the springback runs did not contribute to the final energies.

Of minor concern was the limited precision of values in generated files as compared to LS-DYNA's internal databases. However, the agreement between analysis types indicates that the aggregate effects of these limitations are small.

Thus, where fully understood and implemented correctly, springback analyses are a powerful tool for expediting complex series of simulations.

6 Literature

[1] LSTC: "LS-DYNA Keyword User's Manual", Version 971 R5.1, April 2011
[2] OASYS Ltd: "PRIMER User Manual", Version 10.0, June 2011