Advances in non-linear seismic analysis techniques

Robin Dickenson, November 2020

Introduction

Who

- Robin Dickenson
  - 20 years doing structural simulation
  - Nuclear, Aerospace and Rail industries

- Senior Engineer at Atkins
  - Member of the SNC-Lavalin group
  - Provides engineering services to many industries

What

- Atkins working with EDF
- Seismic assessment of AGR graphite cores
- Specialised application of finite element analysis

The views in this presentation are those of the author and not necessarily of EDF.

Advanced Gas-Cooled Reactors (AGRs)

EDF has a fleet of 7 AGR stations

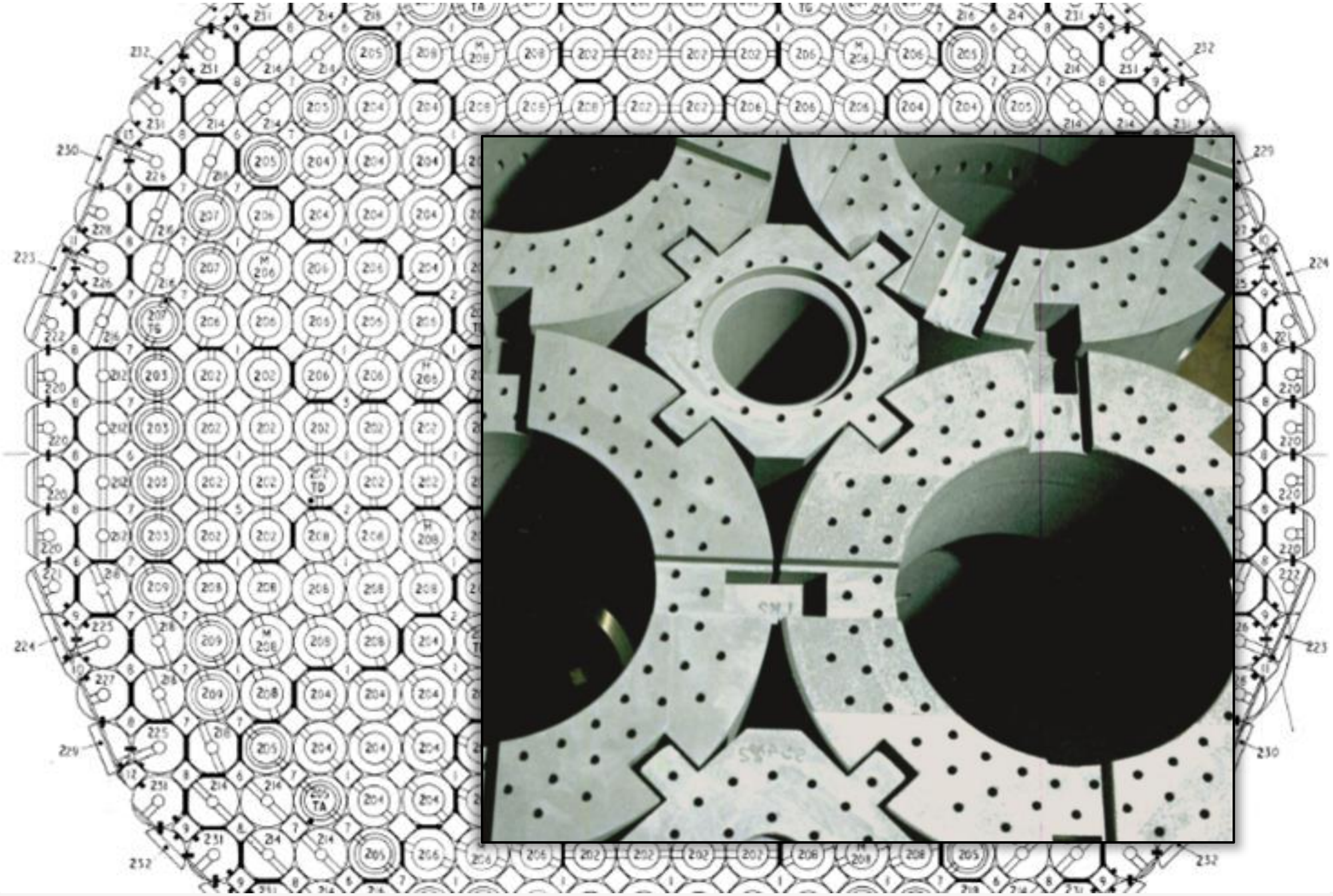
- Each with 2 reactors
- 4 Designs

Array of graphite bricks (moderator)

Channels for fuel and control rods

Keying system

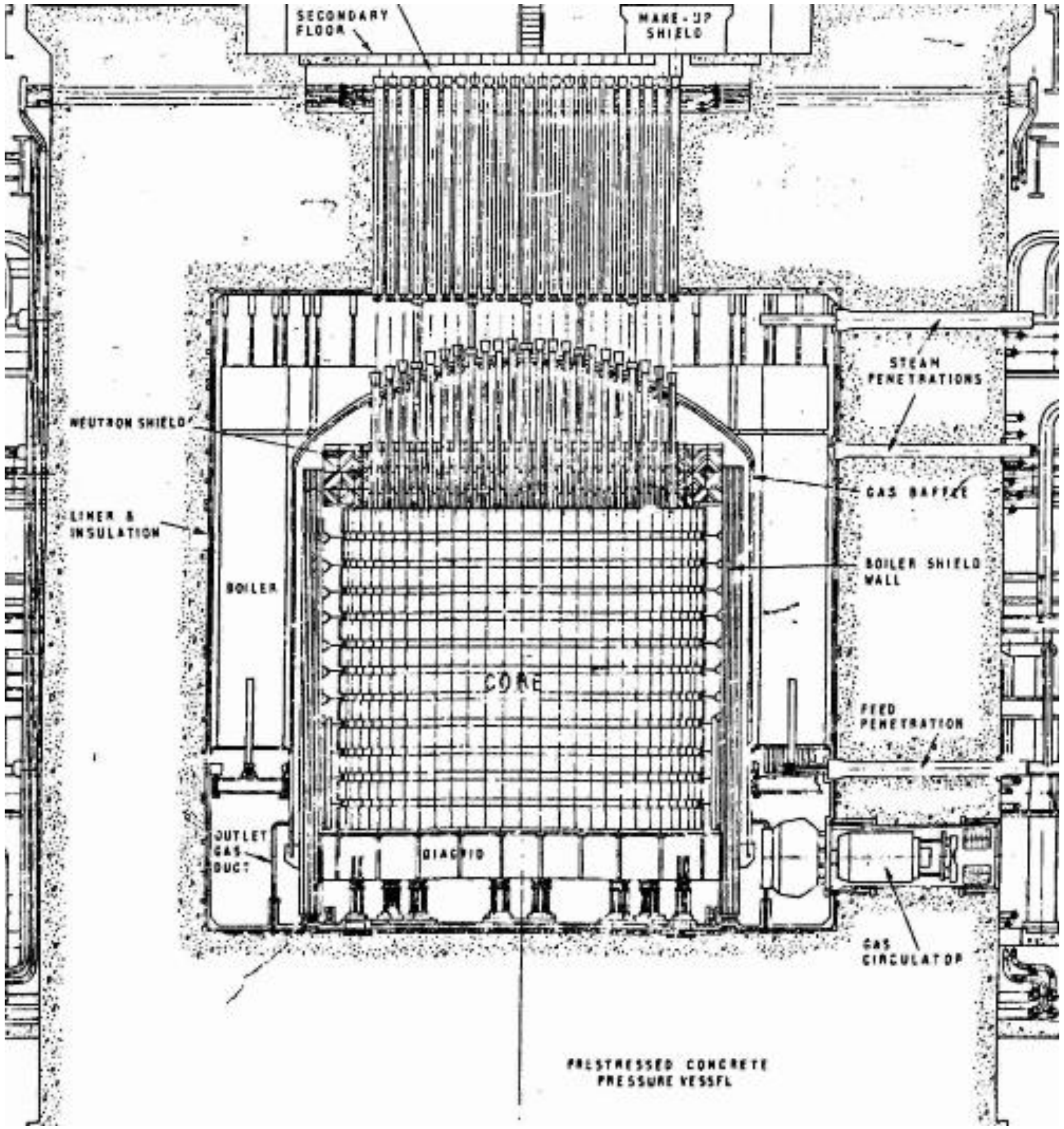
- Maintain relative position
- Accommodate thermal expansion



The Question

Could the reactor be shut down following a 1 in 10,000 year earthquake?

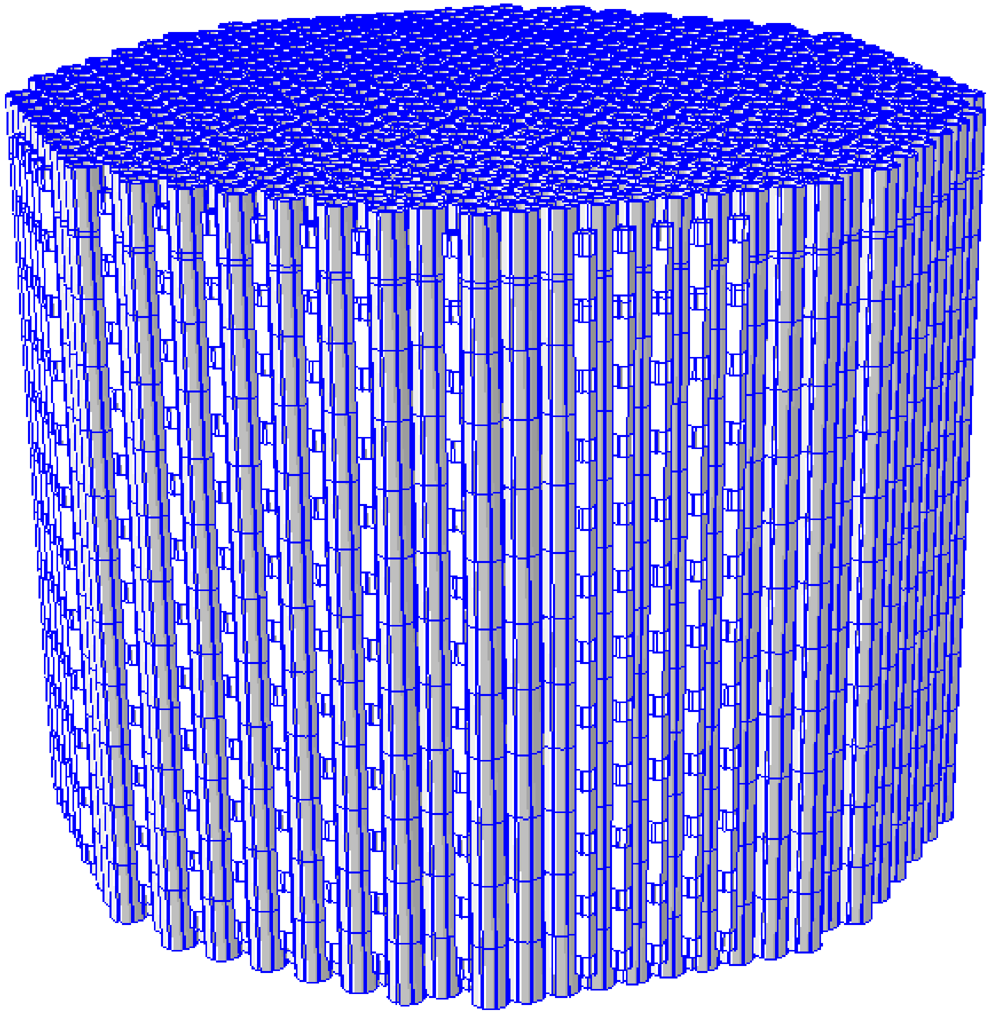
- Primary shutdown by full insertion of control rods.
- Seismic event could disturb the graphite bricks and distort the control rod channels.
- Would the distortion impede the control rods?



The Problem

Computationally expensive:

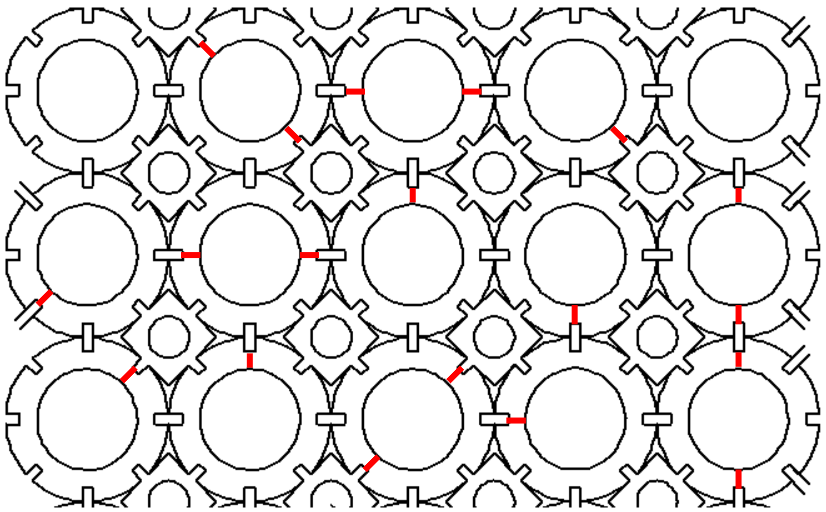
- 40,000+ graphite components
- Interacting through clearance contact (very non-linear)
- Transient loading
- Long event (10 to 30 seconds)

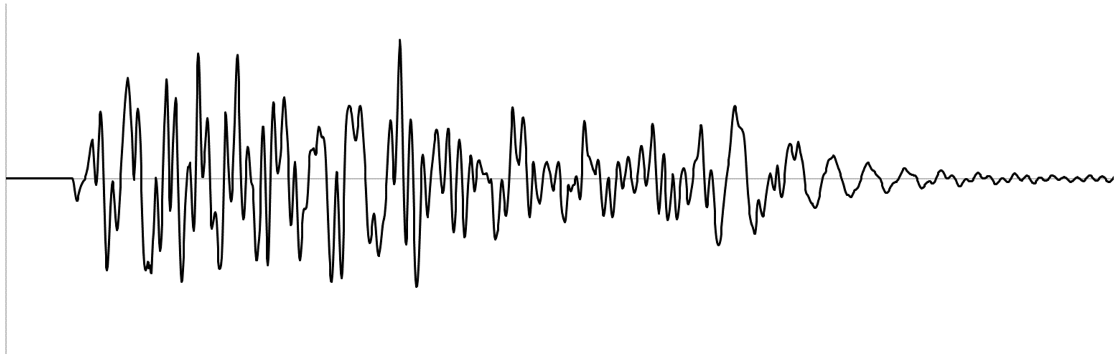


The Problem

Lots of configurations / analyses:

- Different AGR designs
- Brick geometry, stiffness and strength depend on location and core age
- Graphite bricks can crack late in life
  - *Changes geometry and connectivity*
- Bounding uncertainties:
  - *Seismic event*
  - *Ground / building response*
  - *Future core state*





The Problem

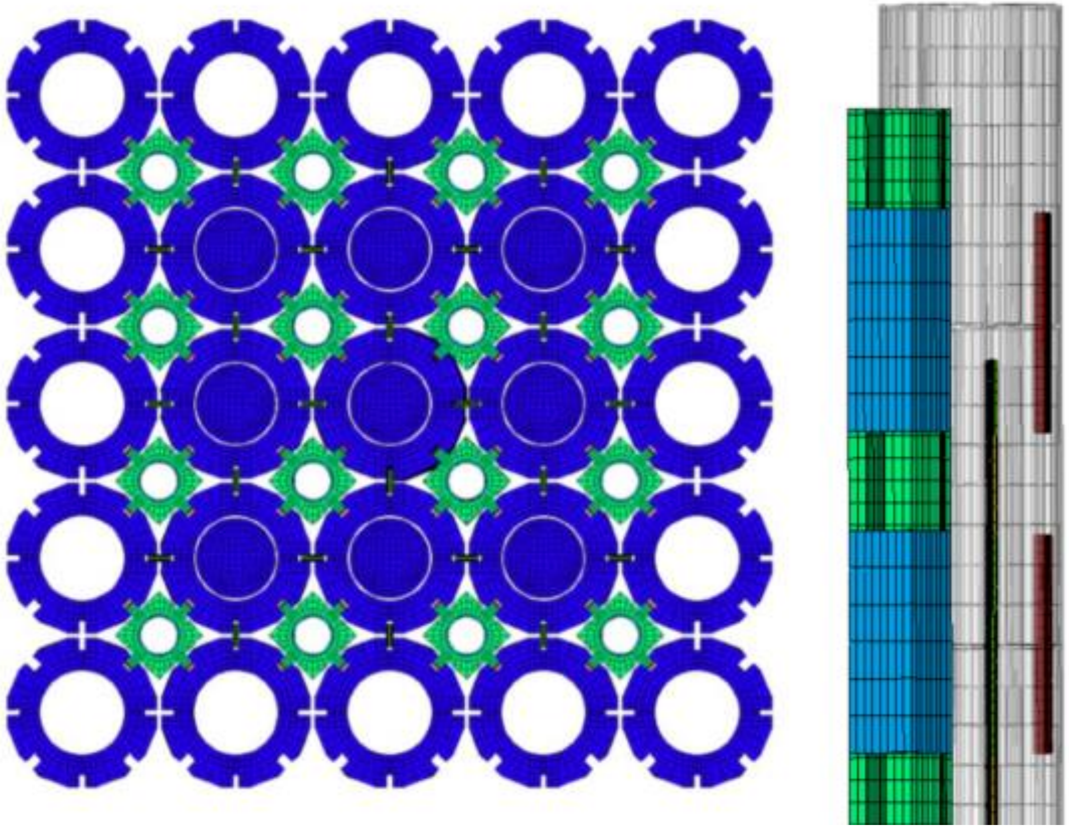
A class of problem typically solved with finite element analysis.

Naïve approach:

- Mesh graphite bricks with solid elements
- Use generic contact algorithm

But…

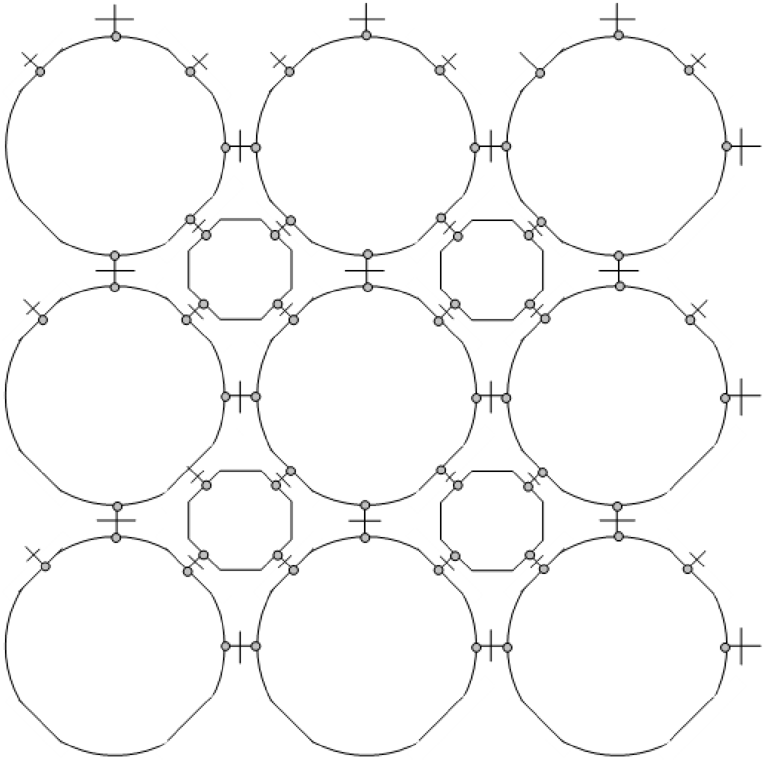
- Brick features need small elements
  - Lots of elements
  - Small time increments
  - Very high computational cost
    ≈50,000 CPU hrs per analysis (estimated)



The GCORE Solution

GCORE

- Method + toolset for seismic analysis of AGR cores
- Developed by Atkins for EDF
- Explicit time integration FEA
- Graphite bricks represented by rigid bodies
- Interactions modelled with discrete elements
  - e.g. non-linear springs / dampers
- Automated model generation / post-processing
- Reasonable computational cost
  ≈100 CPU hrs per analysis



GCORE History

Late 1990s:

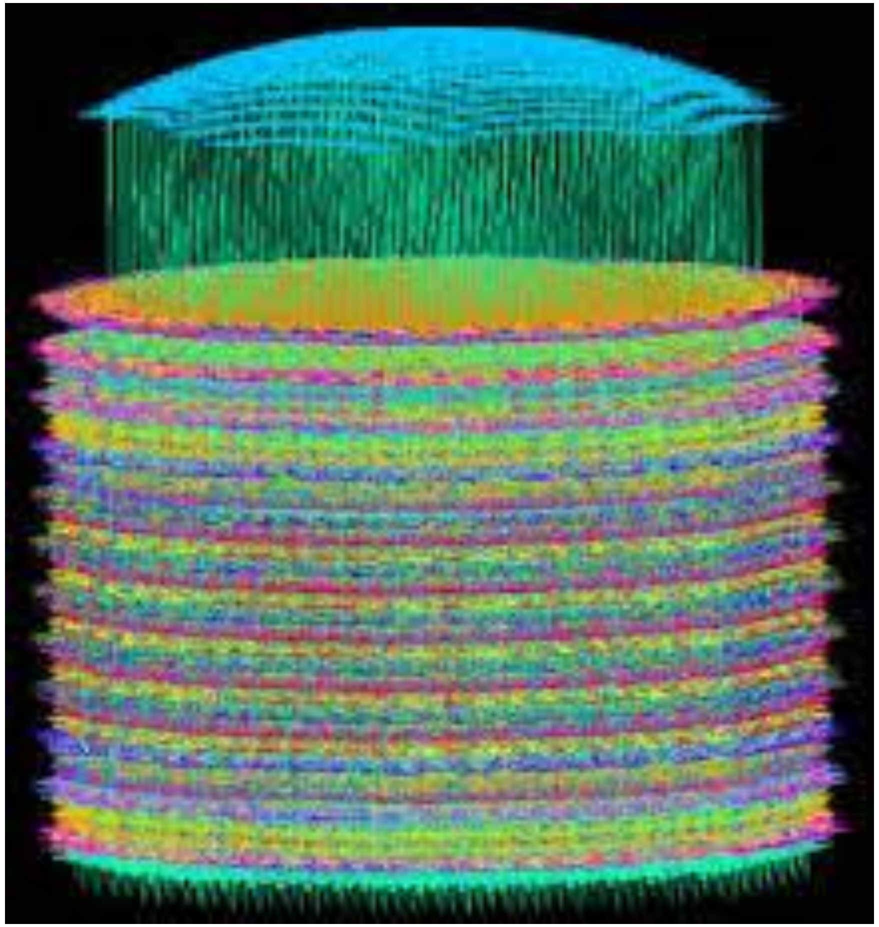
- LS-DYNA solver
- Fixed direction 1D spring/damper elements
- Assessing idealisation with small models
  - Single column or 2D partial array

2004:

- 3D model of half-core (assumed symmetric)
- Automation of pre / post-processing

2005 – 2015:

- Add fuel stringers, guide tubes, supporting structure, etc
- Extend to full-core
- Adapted for different station designs



The Damage Problem

Some key/keyways could be overloaded during the seismic event.

- Changes load path and allows greater displacement
- Need to remove connection from model
- Difficult to automate with LS-DYNA discrete elements
  - Connection modelled with multiple elements
  - Need to sum loads then deactivate all
- Initial solution:
  - Iterate analysis manually
    - *Run ↺↻ Remove overloaded elements*
  - Time consuming
  - Excessively conservative

Abaqus User Elements

2015: Started transition to Abaqus/Explicit as an alternative to LS-DYNA.

- Considered connector elements
  - Adaptable but still with limitations
  - Slow
- User Element
  - Fortran subroutine (VUEL)
  - Extend Abaqus capability
  - Bespoke behaviour
  - Fast

Inputs

- Element properties
- Node displacements and velocities

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VUEL Subroutine

- Called for each user element
- At each time increment

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Return

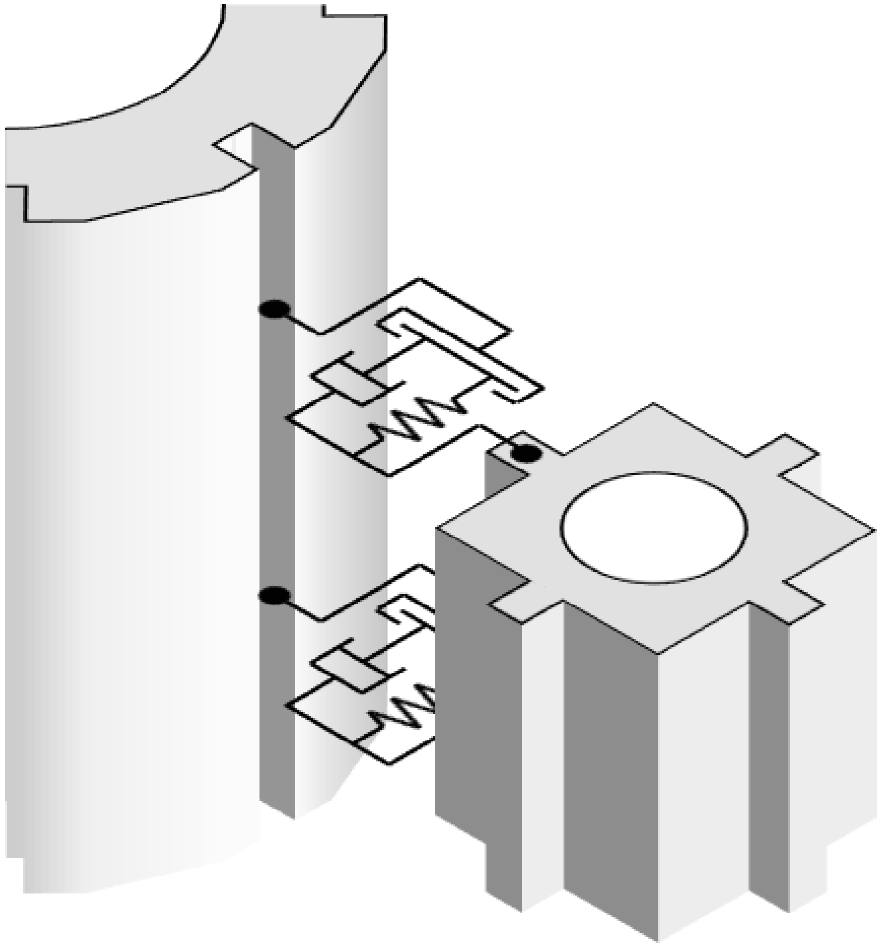
- Forces on Nodes

The first GCORE user elements

- Initially written to replicate the behaviour of the LS-DYNA idealisation
  - 1 VUEL replaces 1D spring + damper elements

- Extended to allow key/keyway failure
  - Multiple spring/dampers grouped
  - Sum loads to detect overload
  - Whole connection removed following overload

- Add friction normal to contact load

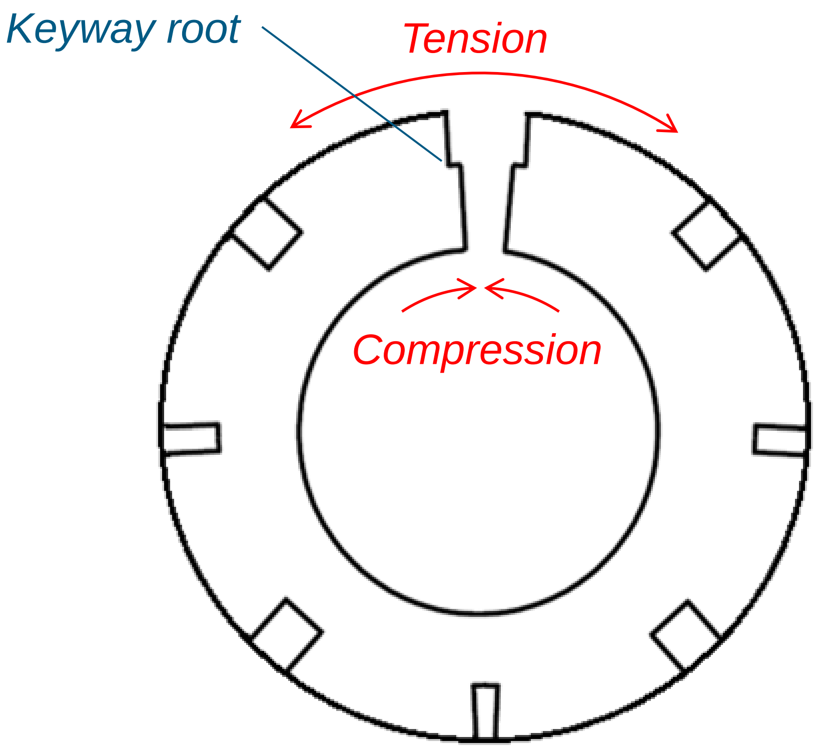


Keyway Root Cracking

Prolonged radiation induces internal stresses in the graphite bricks.

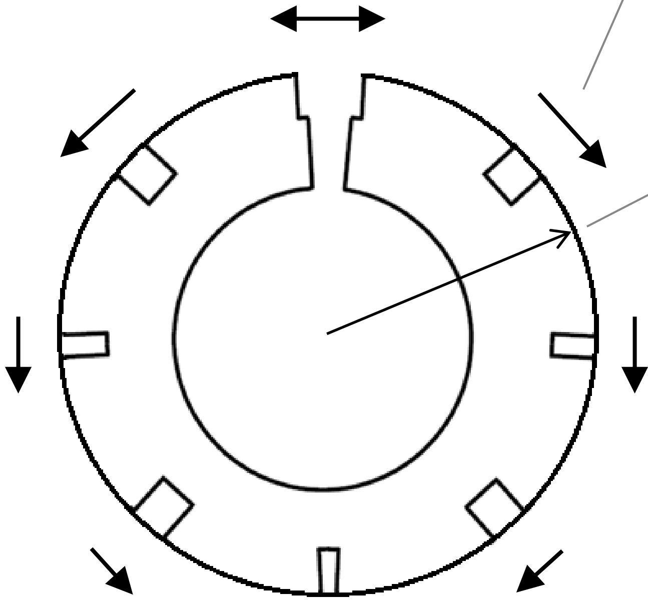
Late in life:

- Tensile hoop stress on outside of brick
- Crack initiates at radial keyway root
- Propagates:
  - To full height
  - Through to bore
- Crack opens wider with continued radiation



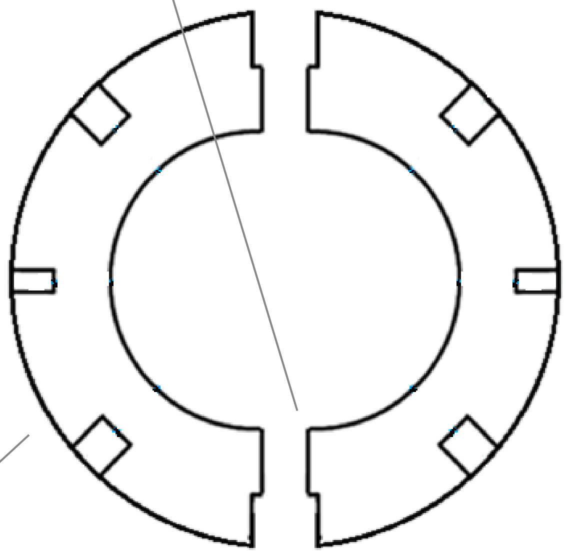
Initially considered 2 types of crack configuration

Single Cracked Brick (SCB)



8 Possible orientations

Double Cracked Brick (DCB)



4 Possible orientations

Multiply Cracked Bricks (MCBs)

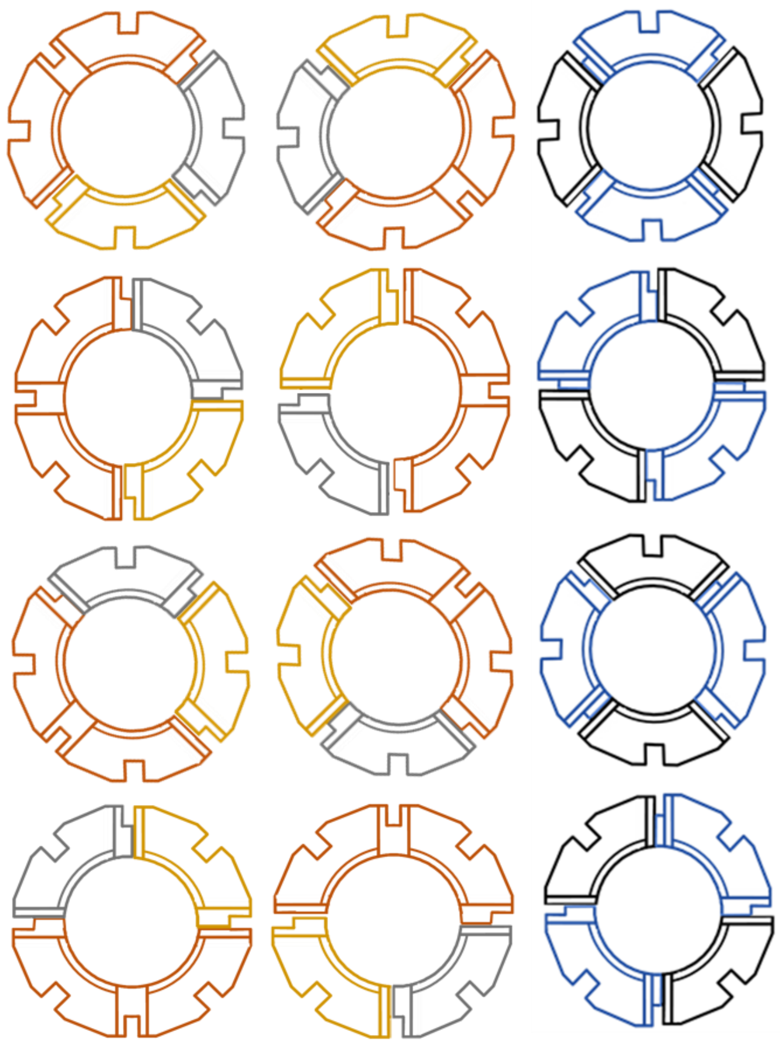
Following inspections at Hunterston B in 2018, consider:

- Bricks with more than 2 radial keyway cracks

Big increase in number of possible:

- Crack configurations
- Brick segment shapes
- Arrangements of neighbouring bricks

How to manage increased complexity?

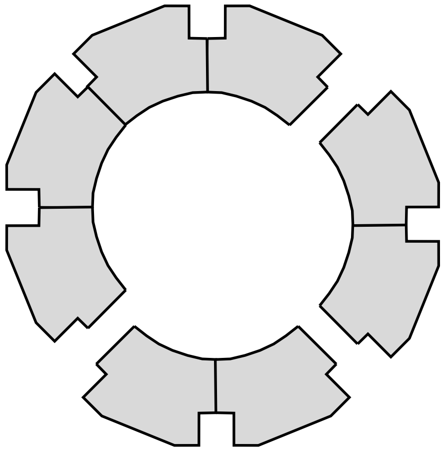


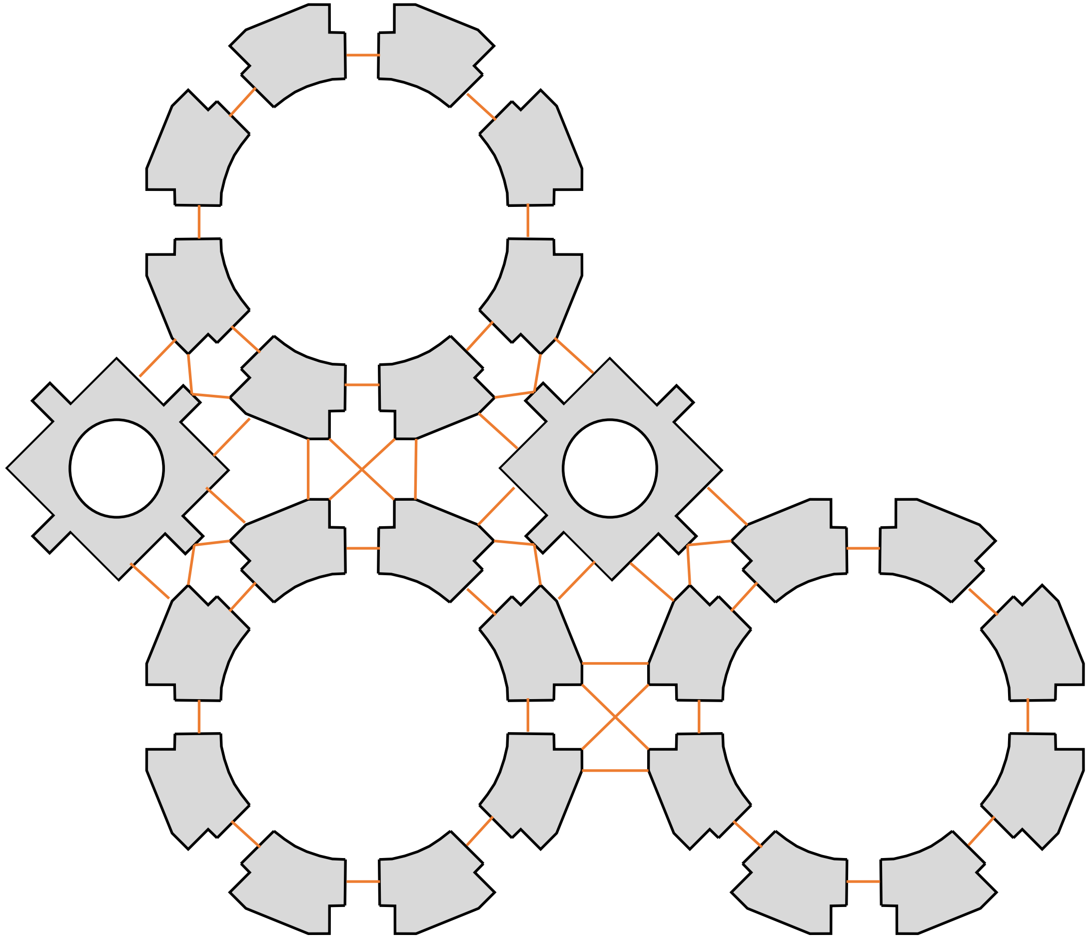
New GCORE Architecture

Models based on “octants” rather than bricks.

Always create the same elements in the same places

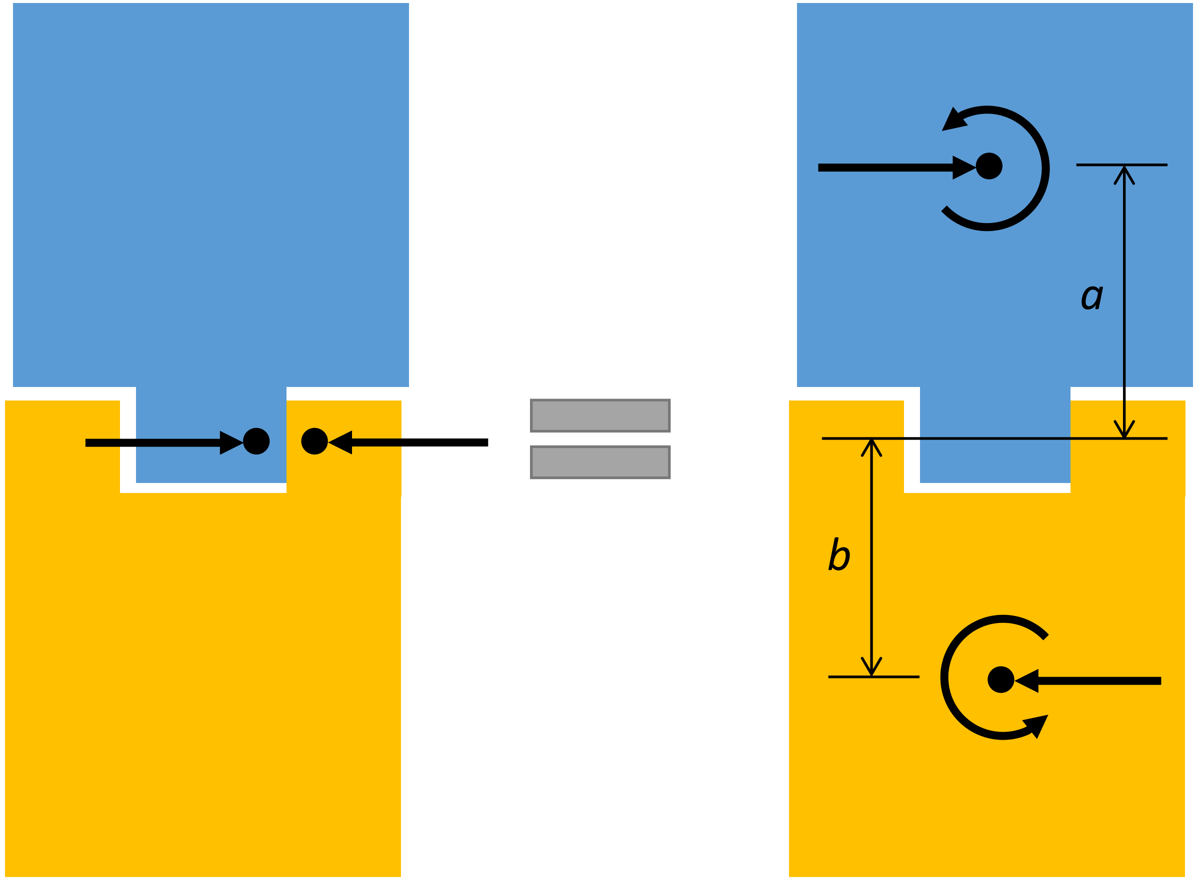
Octant node sets grouped into rigid bodies





New User Elements (VUELs)

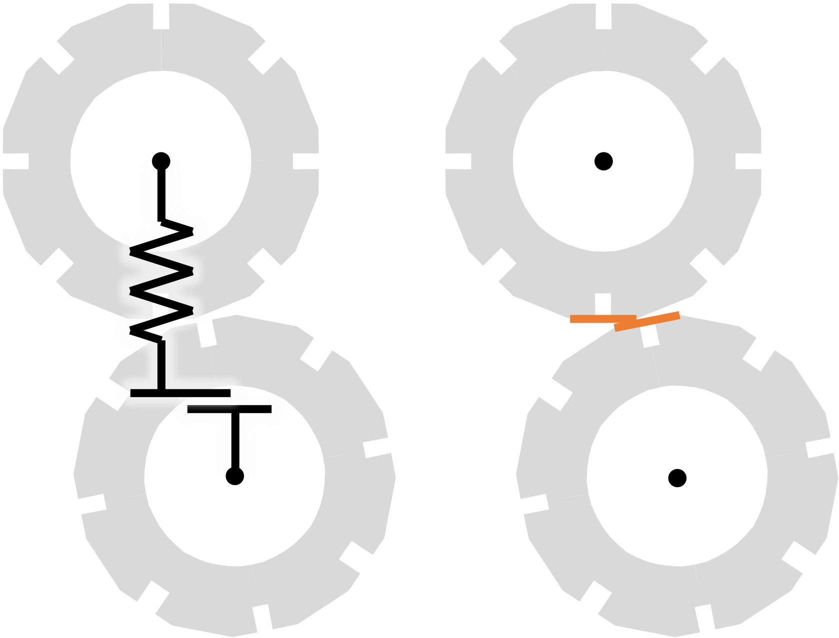
- Move complexity from model generator to VUELs
- Specific VUEL for each type of interaction rather than generic spring + damper
  - 23 VUELs in current library
- Geometry based on properties rather than node positions
  - Reduce number of nodes
  - Simpler connectivity definition
  - Equivalent force system on central node

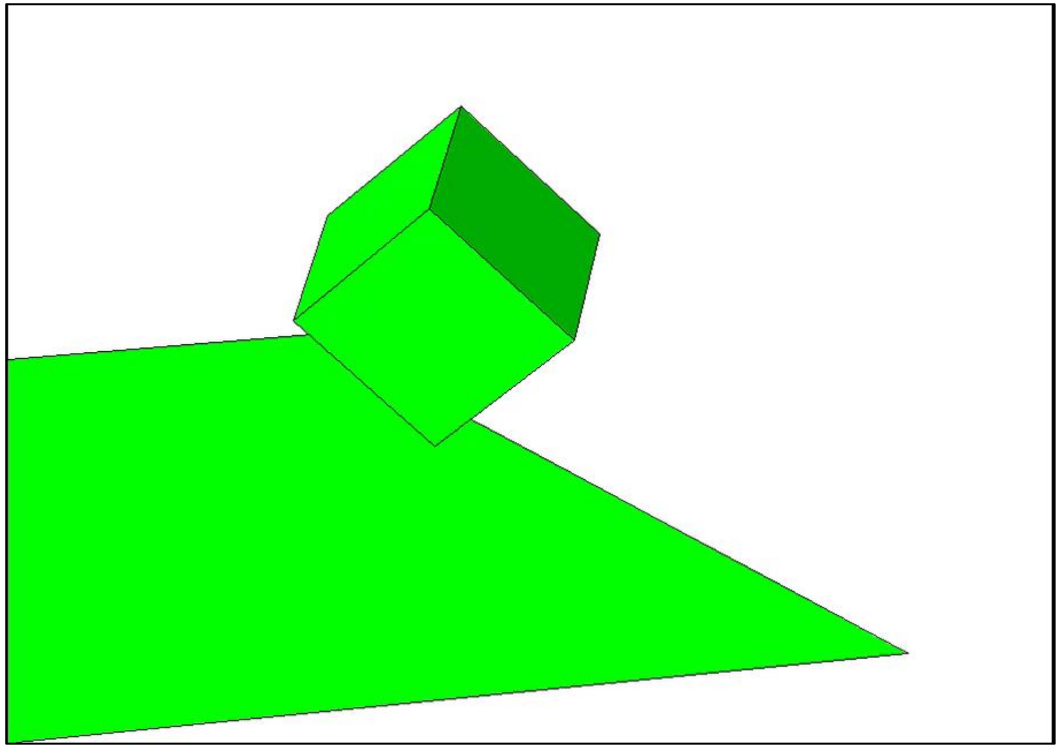


New User Elements (VUELs)

Increase range of validity

› 3D contact algorithm instead of 1D element





New User Elements (VUELs)

Smarter output / post-processing.

Historically:

- All forces and displacements written to file
- High frequency output
  - But still some sampling error
- Large files
- Long post-processing times

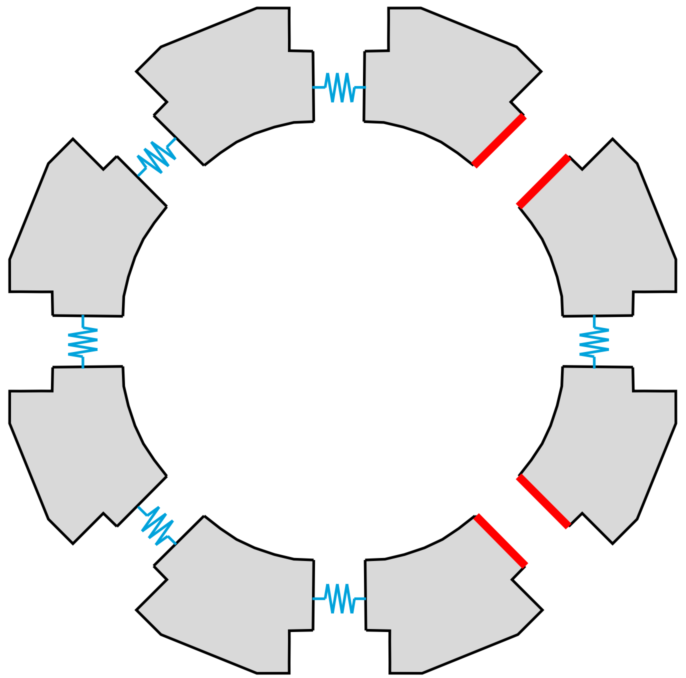
Now:

- Only report key metrics
  - Max force over whole analysis
- Reduced file sizes
- No sampling error
- Faster post-processing

Current Development

Cracking as runtime damage

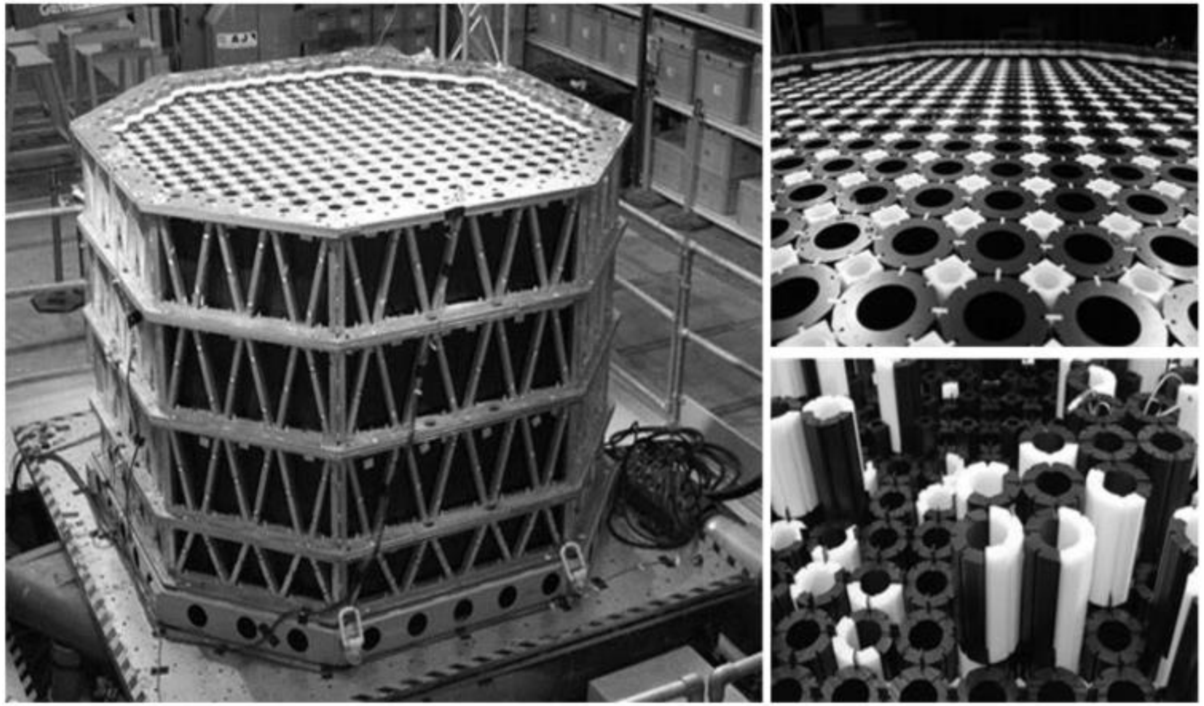
- Each octant is a separate rigid body
- VUEL holds octants together
  - Release if keyway crack initiated
- Cracks initiated by overloads on end-face keys
  - Could be extended to use other triggers



Validation

Validation against test

- Quarter-scale model using plastic bricks
- On shaking table at University of Bristol
- Instrumentation tracks brick displacements
- GCORE approach used to simulate test
- Good correlation between GCORE and test



Visualisation

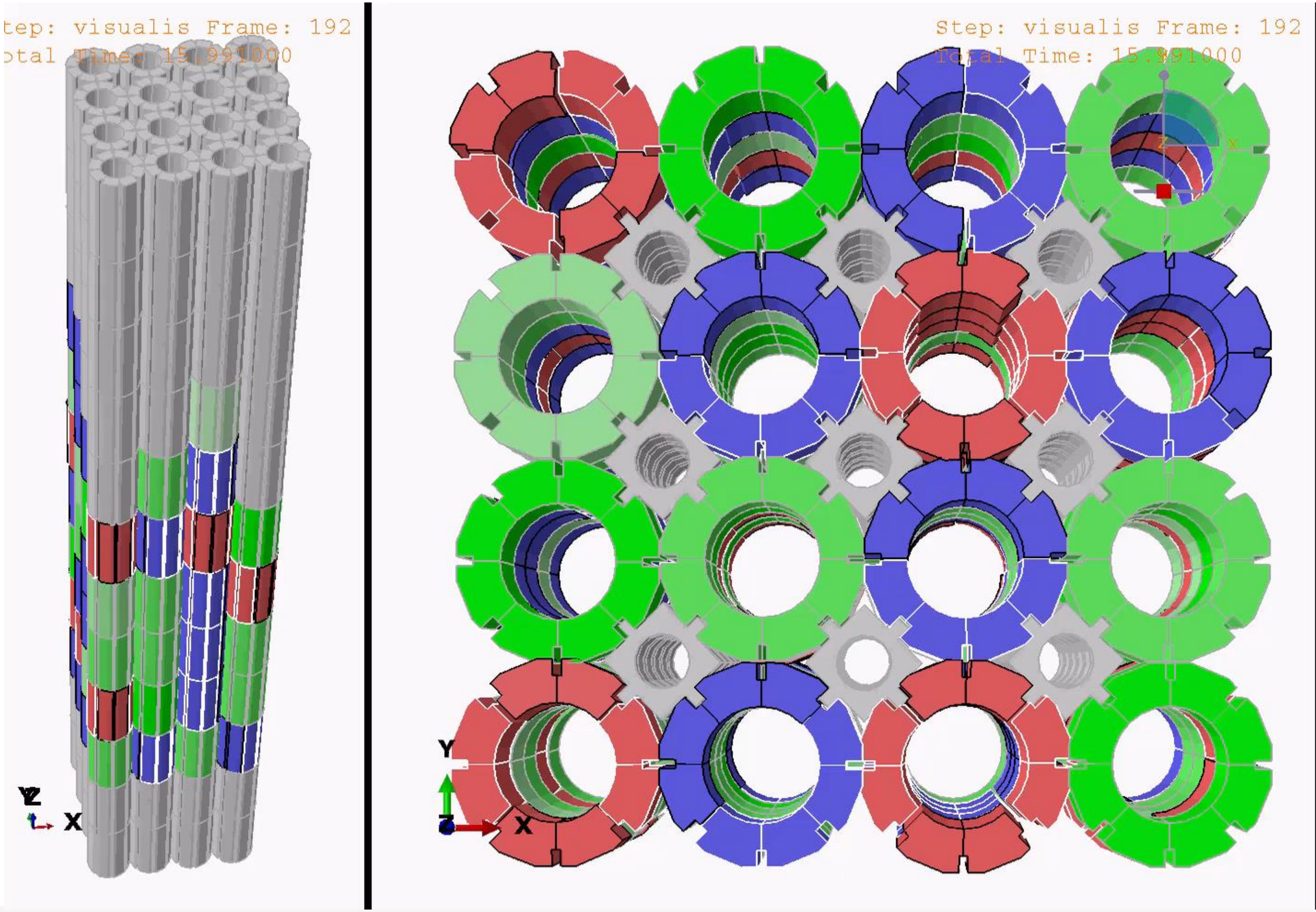
VUELs cannot be visualised in post-processing tools.

Use Abaqus DISPLAY BODY

- Apply GCORE displacements to brick geometry

This example shows:

- 4x4 Fuel Brick columns
- From centre of core model
- Colours show brick crack type
  - **Uncracked, SCB, DCB, MCB**



GCORE Summary

- Simulate seismic response of AGR core
- Abaqus/Explicit solver
- Extensive package of user subroutines
  - Model interactions between graphite bricks
    - *3D contact of complex geometry*
    - *Runtime damage*
  - Efficient output of results
- Fast solution of difficult problem
- Wider system of automation tools
  - Model generation
  - Results processing
- Approach validated against test

Thanks

- Alan Steer, EDF
- John Sawyer and GCORE team, Atkins

Our values are the essence of our company's identity. They represent how we act, speak and behave together, and how we engage with our clients and stakeholders.

SAFETY

We put safety at the heart of everything we do, to safeguard people, assets and the environment.

INTEGRITY

We do the right thing, no matter what, and are accountable for our actions.

COLLABORATION

We work together and embrace each other's unique contribution to deliver amazing results for all.

INNOVATION

We redefine engineering by thinking boldly, proudly and differently.