***FY14 K*-Solution Update**

AFGROW Workshop

US Air Force Academy CAStLE

Gregory A. Shoales, Director

James M. Greer, Jr., Technical Director

Börje Andersson, Principal Investigator

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Overview of FY14 Activities

- **Evaluation of new HPC computer**
- **New *K*-solutions**
- **Related work in *K* solutions**
- **Discussion**

EVALUATION OF NEW HPC COMPUTER

Evaluation of New HPC Computer

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- **New HPC Computers 2014: Armstrong and Shepard (sister systems)**
  - **Cray XC30 with 30,144 compute cores, 124 Xeon Phi nodes, (and on Armstrong 32 NVIDIA K40 nodes). Peak performance :** $0.75 \cdot 10^{15}$ **FLOPs (each system)**

- **Todays HPC Computer used for calculation of FY14 *K*-factors: Garnet**
  - **Cray XE6 with 150,912 compute cores.**
    Peak performance: $1.50 \cdot 10^{15}$ **FLOPs**
    Example: S Fawaz used Garnet to execute many single 5000 core jobs (>200 crack configurations simultaneously) on Garnet when deriving *K*-factors FY14.
  - **Garnet will be de-commissioned 2015**

Evaluation of New HPC Computers (cont'd)

- **Börje Andersson (PI) participated as a Pioneer User and evaluator of the Armstrong/Shepard system**
  - **Two software were tested on Armstrong**
    - **#1: STRIPE (**FE-code**)**
      - "On Armstrong we have in the pioneering period measured the highest I/O speeds and highest TFLOP-speeds ever seen on any HPC hardware running STRIPE".
      - Able to solve problems of size a few hundred-million DOF problems ***in-core, 25%-50% faster then out-of-core*** (first tests – can probably be improved by 2x or 3x)
      - Was able to port from Garnet (Cray XE6) in less than 1 hour
    - **#2: BABEL (**multi-level damage assessment, the system is used to derive the FY14 K_I – solutions**)**

Evaluation of New HPC Computers (cont'd)
STRIPE Large scale example

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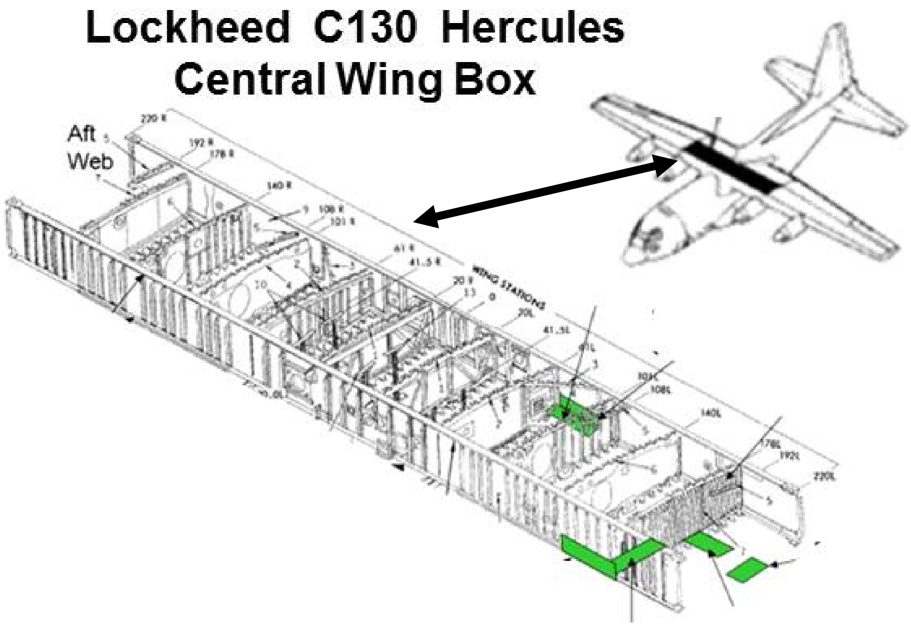
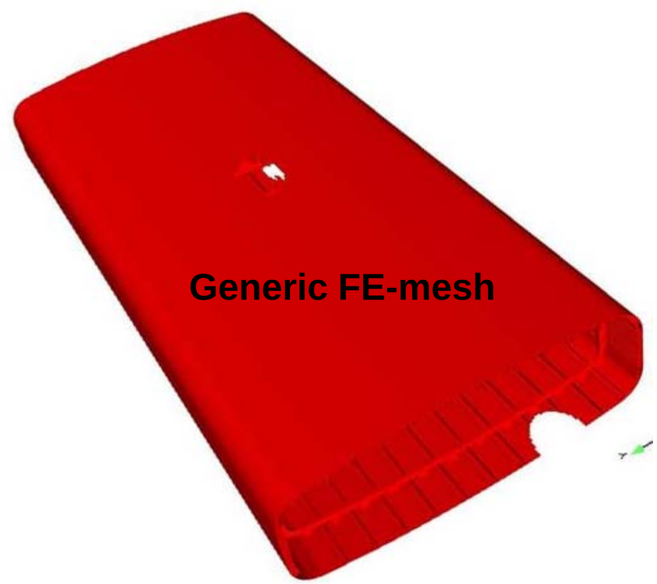


Generic CWB Mesh:

L=10m, 20 frames, 60 stringers, 25k rivets modelled as 3D objects

FE-Mesh: 7M HEX-elements

Model sizes: 0.6 GDOF's (*p=5* elements)



Evaluation of New HPC Computers (cont'd)
The largest STRIPE benchmark case

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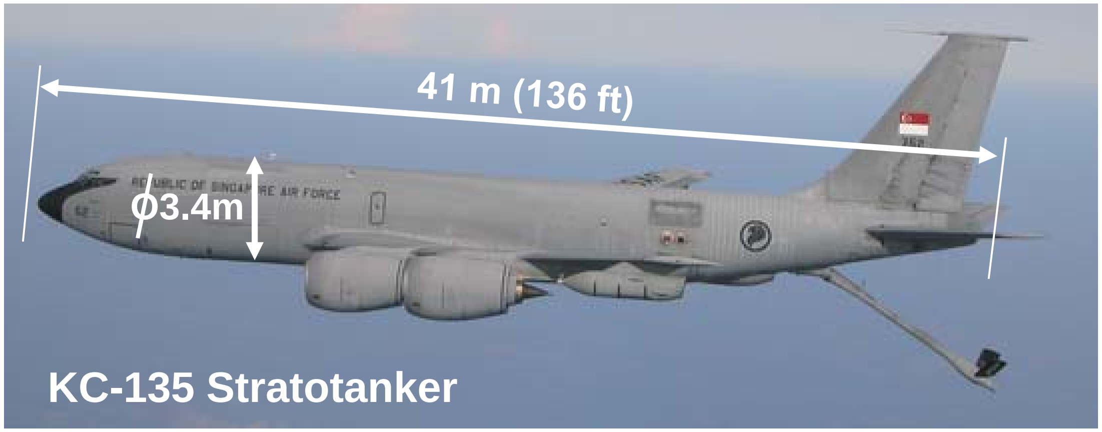
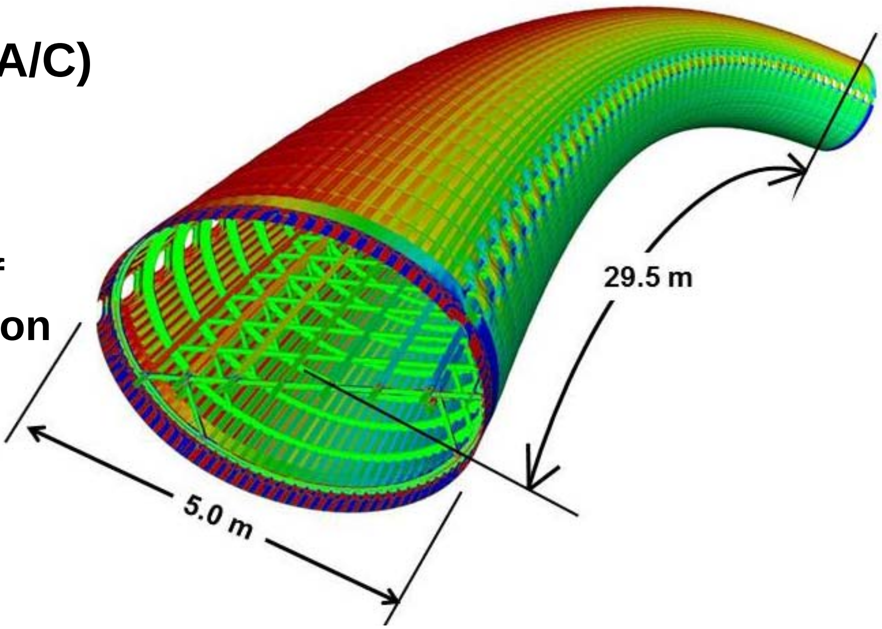
Model Scenario: Stress, fatigue and residual strength analysis of full A/C



Generic FE-model of fuselage (civil A/C)

Mesh has 40 million HEX finite elements.
Element size 4mm x 4mm x thickness.
The model having 2.02 billion degrees of freedom was solved (STRIPE) in 3 hours on Shepard system using 21600 cores in a single run.



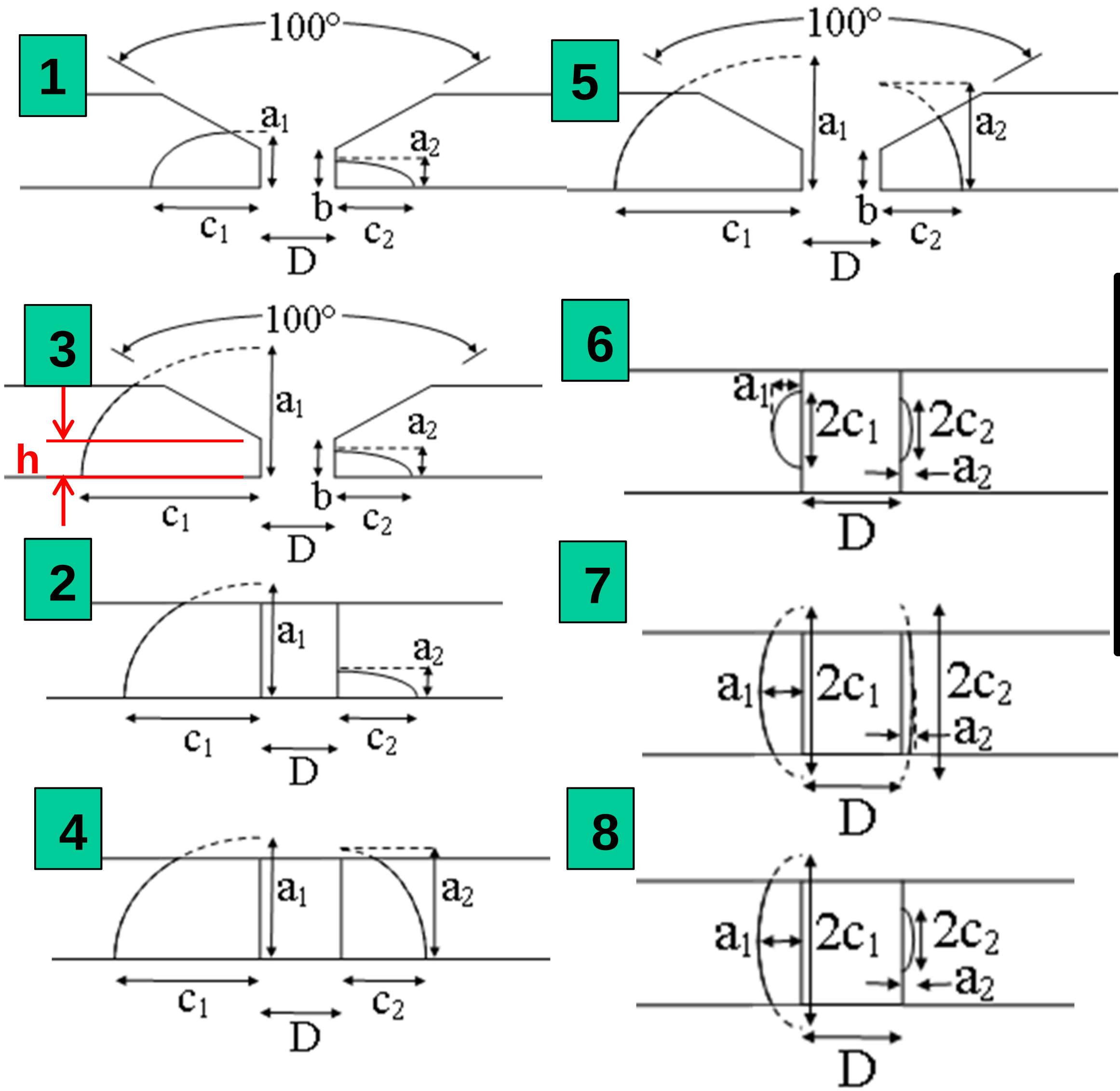
Evaluation of New HPC Computers (cont'd)
Large scale models

HPC-Hardware	Structure	No of HEX finite elements/ *p*-level	Problem Size (millions of unknowns)	Computational Nodes/Cores	Wall Time (hr)
Armstrong	Wingbox	7M *p*=5	607	400/9600	3
Hawk (2009)	*Wingbox*	*7M* *p=7*	*1381*	*2/1024*	*287*
Armstrong	Fuselage	15M *p*=4	1661	400/9600	6
Armstrong	Fuselage	40M *p*=2	2024	900/21600	3

NEW *K*-SOLUTIONS

Plate *K*-Solutions

Parameter Values



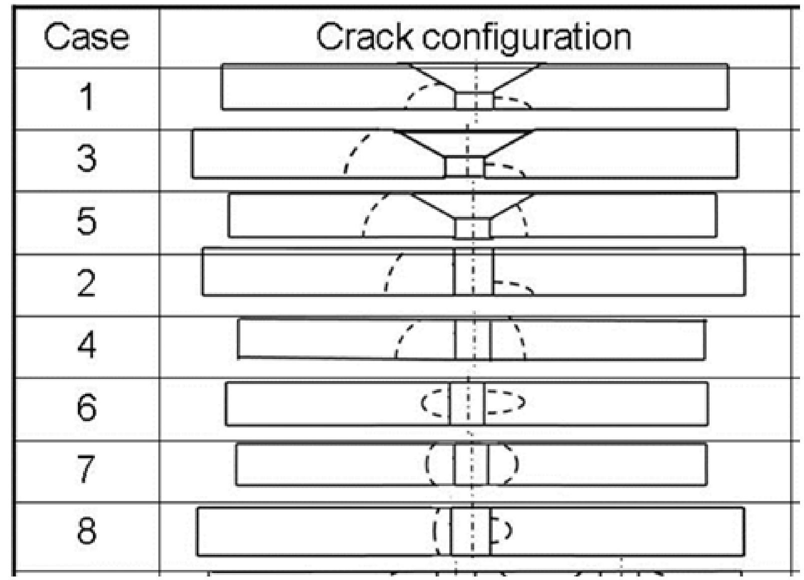
Totally ≈20 M solutions

Parameter values:

$0.075 < R/t < 3,$	8 values
$0.1 \le a/c \le 10,$	25 values
$0.1 \le a/t \le 0.99,$	11 values
$1.05 \le a/t \le 10,$	7 values
$0.05 \le b/t \le 0.75,$	4 values

New K-Solutions

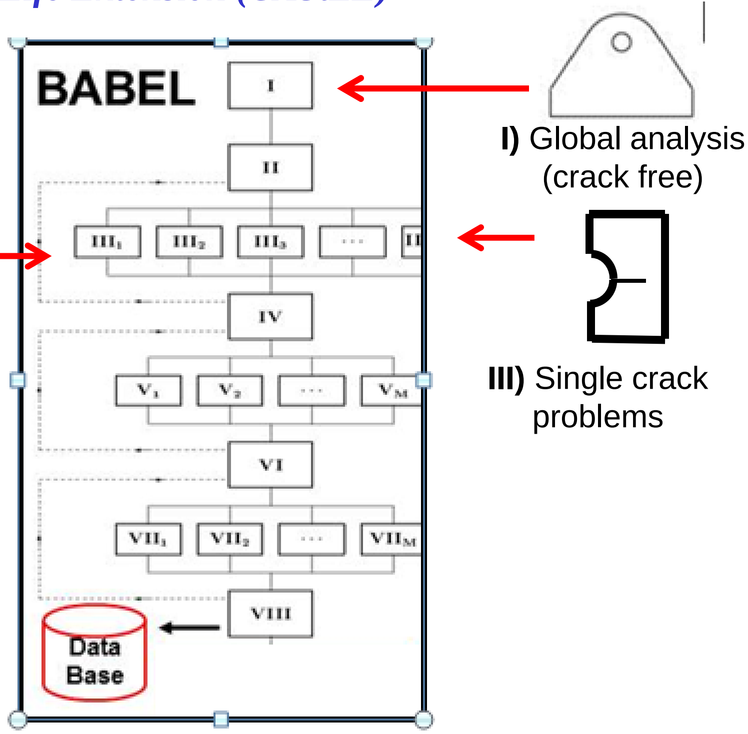
- **Priority order for FY14 was solution cases 2, 4, 1, 3, 5, 6, 8, and 7**
- **Solutions, 2,4,6 8 and 7 have been derived (using BABEL+STRIPE) for the parameter space shown on previous slide and are currently being checked in several ways described below**
- **The mesh generator for cracks intersecting with the conical surface of the countersunk hole had some flaws for extreme *a/c* and is currently being rewritten**
- **All solutions in the table will have been verified during 2014.**

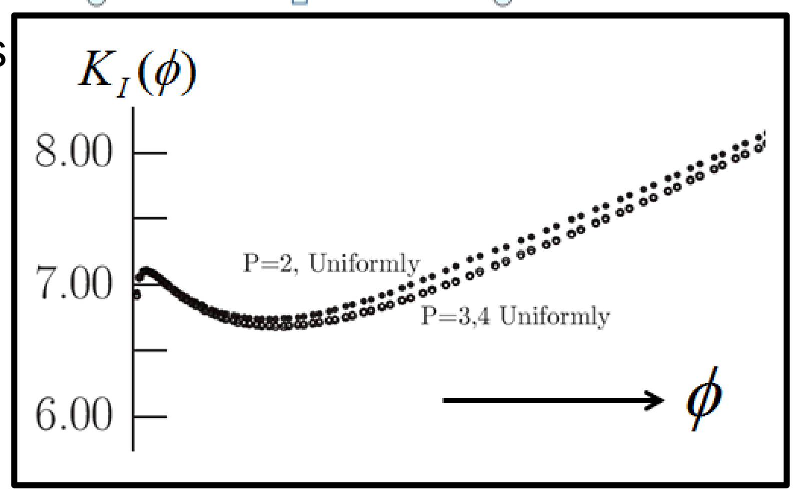


10^{12}

How were solutions checked?

- The strategy selected for verification is based on the fact that the about 10^{12} possible crack scenario are built up by a 3-4 thousand unique single cracks of quarter- or semi-elliptical shape located in the basic domains considered.
- Each of the 3-4 thousand solutions are analysed with *T/Mb* loading. The *hp*-version of the finite element method and so called advanced methods for *K*-evaluation are used which gives exponentially fast convergence to the exact mathematical solution. *K*-solutions were checked for convergence.
- For small cracks (*a/t, c/t, a/R, c/R* small) the solutions on the database can be compared with approximate handbook solutions (Newman), just to guarantee that there is no serious handling error has occurred





10^{12}

How were solutions checked, cont.

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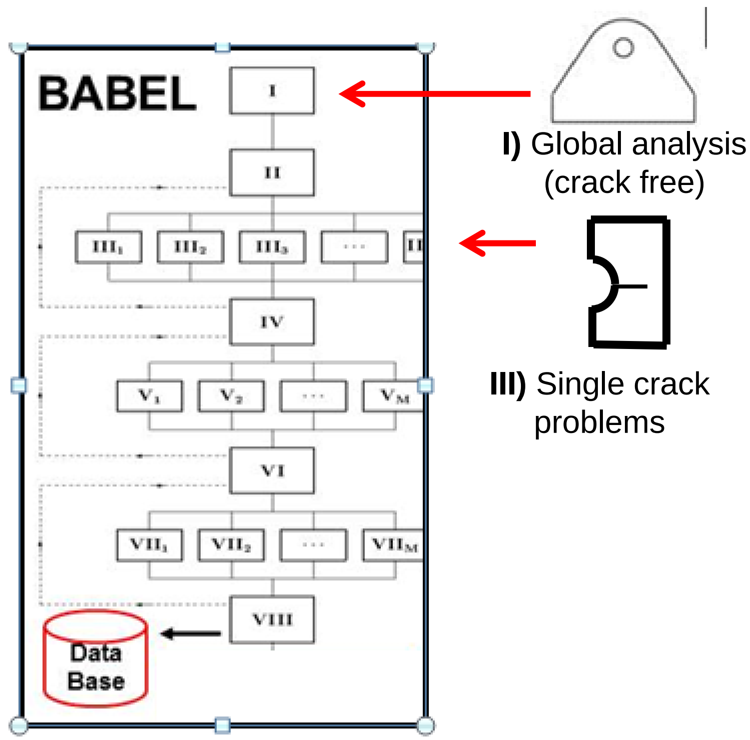
- The BABEL software is quite complex and checking its functionality is tricky. Two time-consuming tests have been performed 2014:
  - Two very different software versions BABEL exists (2010, 2013) with very different data structure. Both where rewritten slightly so cases 2, 4, 1, 3, 5, 6, 8, and 7 could be solved with both systems and the two complete databases could be compared (for the cases mentioned)
  - A special version of the BABEL system was created where the loads applied on levels **I**, and **III** were artificially constructed, i.e. surface tractions and volume loads were calculated from the exact displacement solution:

$$u_i = \sum_{j=0}^{j=5} \sum_{k=0}^{k=5} \sum_{m=0}^{m=5} C_{ijkm} \cdot X^j \cdot Y^k \cdot Z^m$$

where C_{ijkm} are 648 nonzero selected coefficients.

By comparing the analytical displacement solution with FE-solutions* on levels **I**, **III** and **V**, every single number can be controlled with 10-12 digits accuracy. Any scaling, transformation, mapping, software error in BABEL will be detected!!!



* If STRIPE jobs on levels **I, III, V** are solved using *p=6* (or larger) the FE-solution will be identical to the analytical solution (round-off=0).

Plate *K*-Solutions
Which solution spaces are complete?

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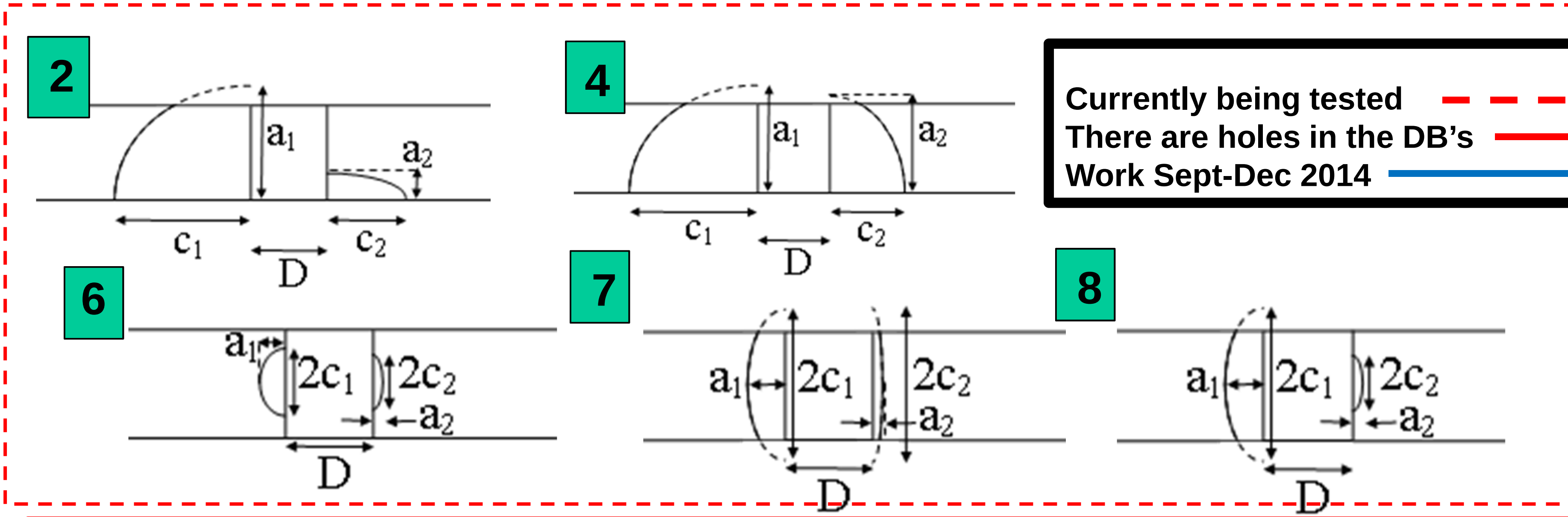
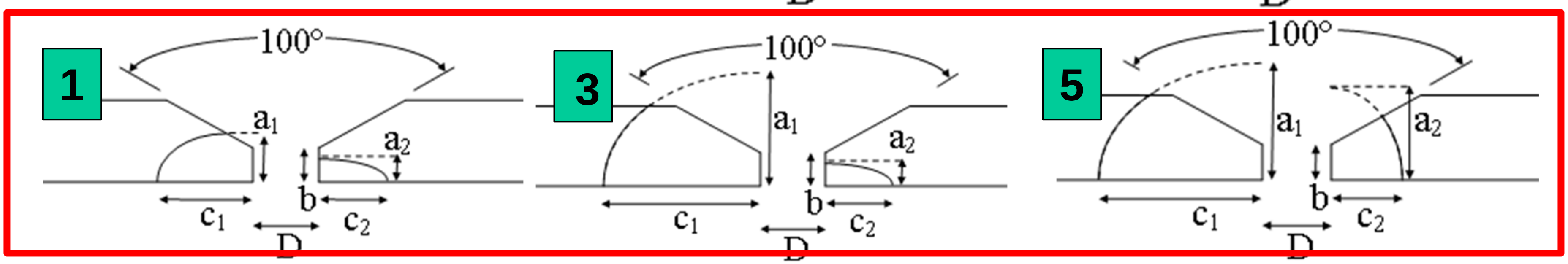
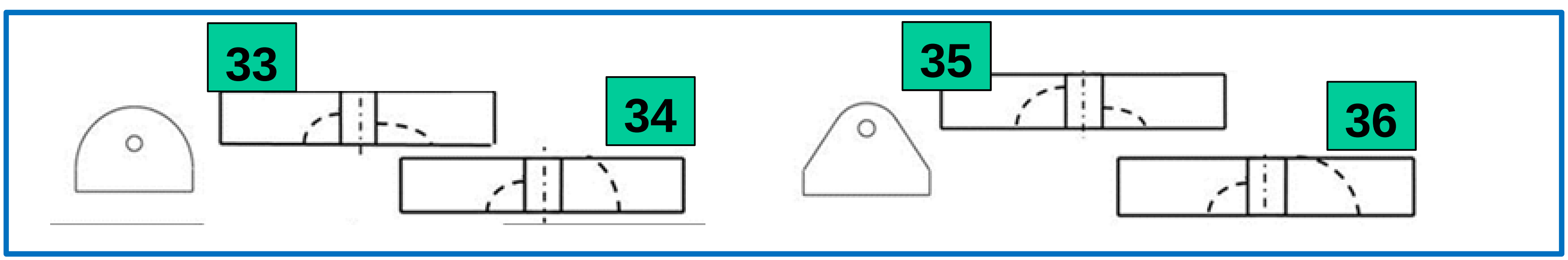
Currently being tested (red dashed line)
There are holes in the DB's (red solid line)
Work Sept-Dec 2014 (blue line)

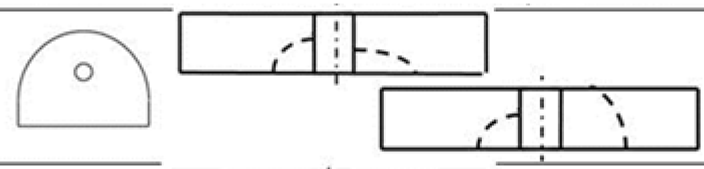
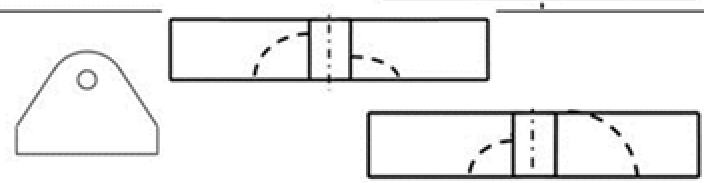






Next *K*-Solutions

- **Lugs, will be available during 2014**
- **Discussion?**

33-34		1-2	0.9 0.7	0.9 0.7
35-36		1-2	1.8 1.6	1.8 1.6

For these small global domains we can solve R/t=4,5,6,7,8,9,10 without large run-off Problems, is there a need?

New K-Solutions
BABEL for generation of *K*-solutions

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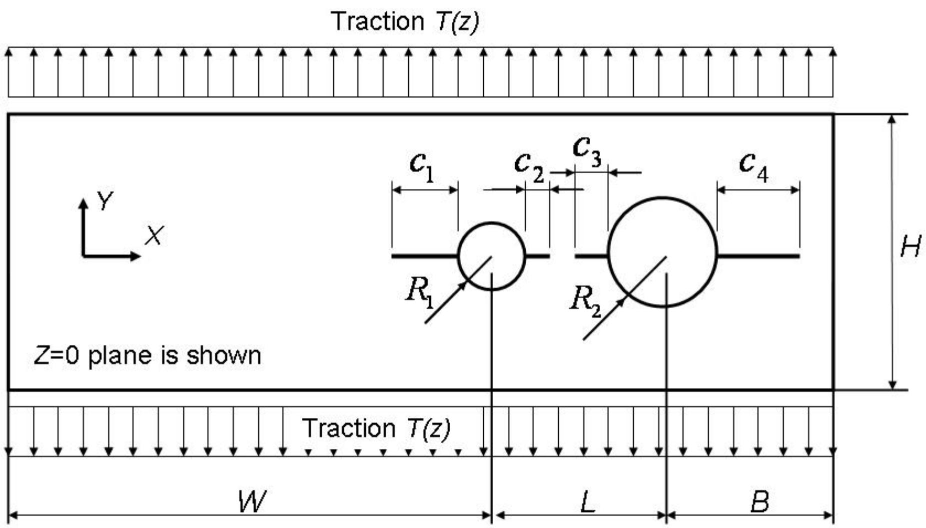

Example: *R/t*=1.0, *L*=3*D*, B=2*D2*, *R1/R2*=0.5

Loc. →	**1**	**2**	**3**	**4**	**Cracks in location 1-4**
Through thickness	74	57	57	50	238
Not -"-	120	118	118	112	468
Sum →	194	175	175	175	706

R/t= 0.075, 0.1, 0.2, 0.333, 0.5, 1.0, 2.0, 3.0 ~~and 6.0~~ $(r = Min\{R_1, R_2\})$

L= 1*D*, 2*D*, 3*D*, 4*D* where $D = Max\{D_1, D_2\}$

B= $1D_2, 2D_2, 3D_2, 4D_2$

R_1 / R_2=0.5, 1.0 and 2.0

Hence there are 384 *global geometries* (8 *r/t*-, 4***L***, 4***B*** and 3 R_1 / R_2-values) to be analysed.

From these 706 single cracks results for 2B crack scenario (1-, 2-, 3- or 4 cracks) are generated using *BABEL*.

Computational effort is not very large:
Of order < 10*k* Cpu-hours to create the result data base on Shepard (Aug 2014)

RELATED WORK IN *K* SOLUTIONS

Related *K*-Solution Work

- **Analysis of findings form teardown analysis programs**
  - **Fleet life assessments—retired aircraft**
  - **Post test assessments—FSFT**
- **One program [very large] is executing a detailed fleet impact analysis of teardown analysis program findings**
- **Large body of finding data infrequently correlates to available K solutions and AFGROW configurations**
  - **Hole with many radial cracks**
  - **Multiple adjacent surface cracks close to a hole**
- **CAStLE will continue to track and report to the AFGROW and ASIP community**
  - **Share new solutions as they are created**
  - **Potential interest for future solutions**

Discussion

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