Effect of damage on performance of composite structures – applications to static and fatigue strength predictions

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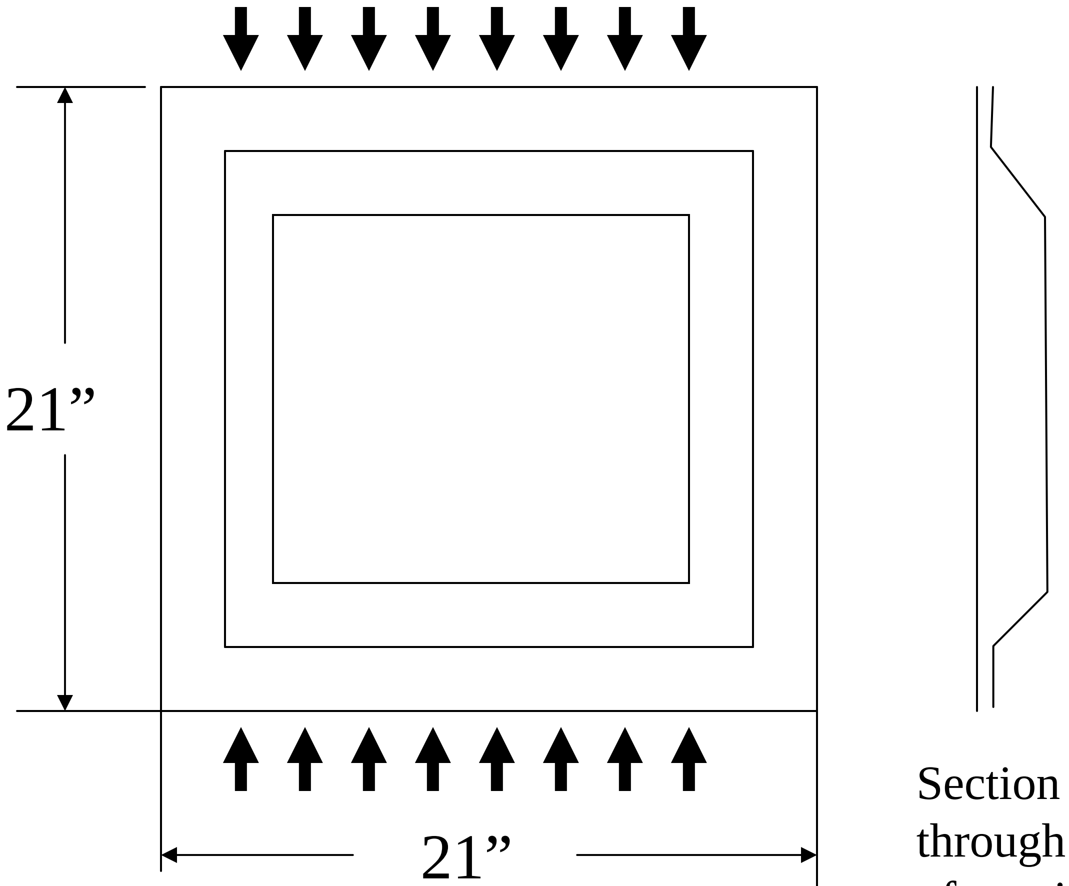
Outline

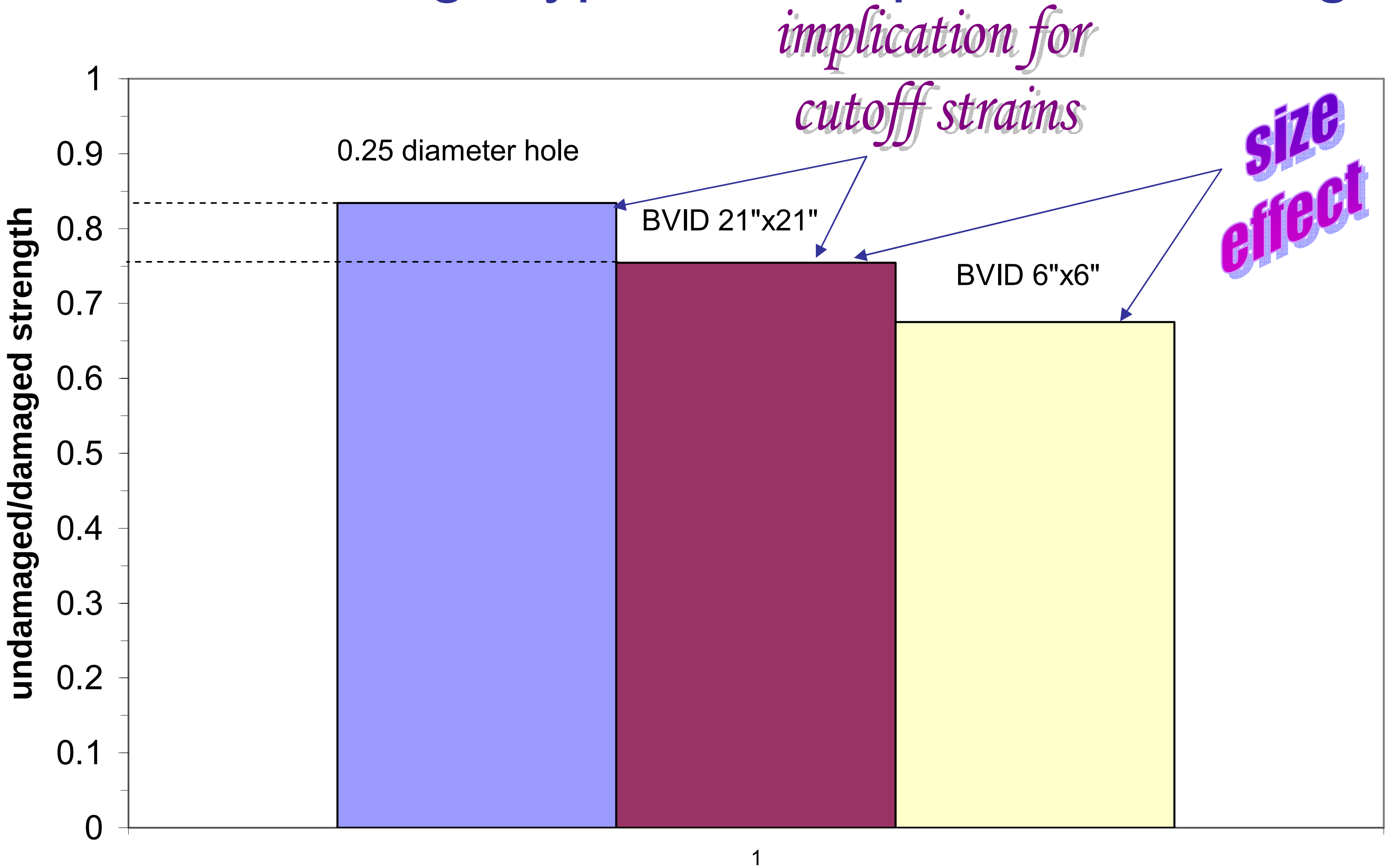
- static
  - open hole
  - BVID
- fatigue
  - constant amplitude
  - B-Basis curve
  - “Goodman diagram”
  - truncation level determination

Sandwich with rampdown

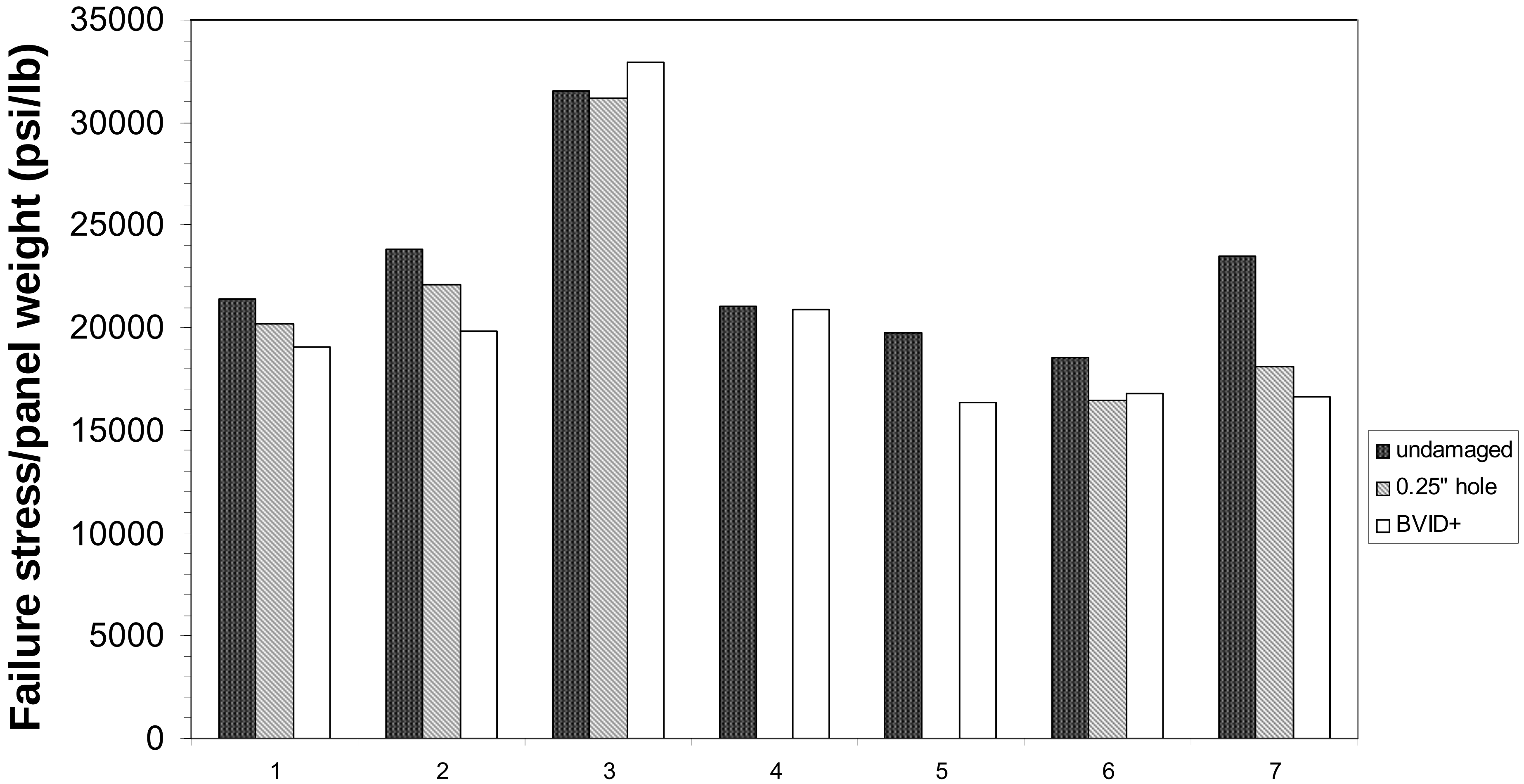


Section cut through center of specimen

Effect of damage type on compression strength

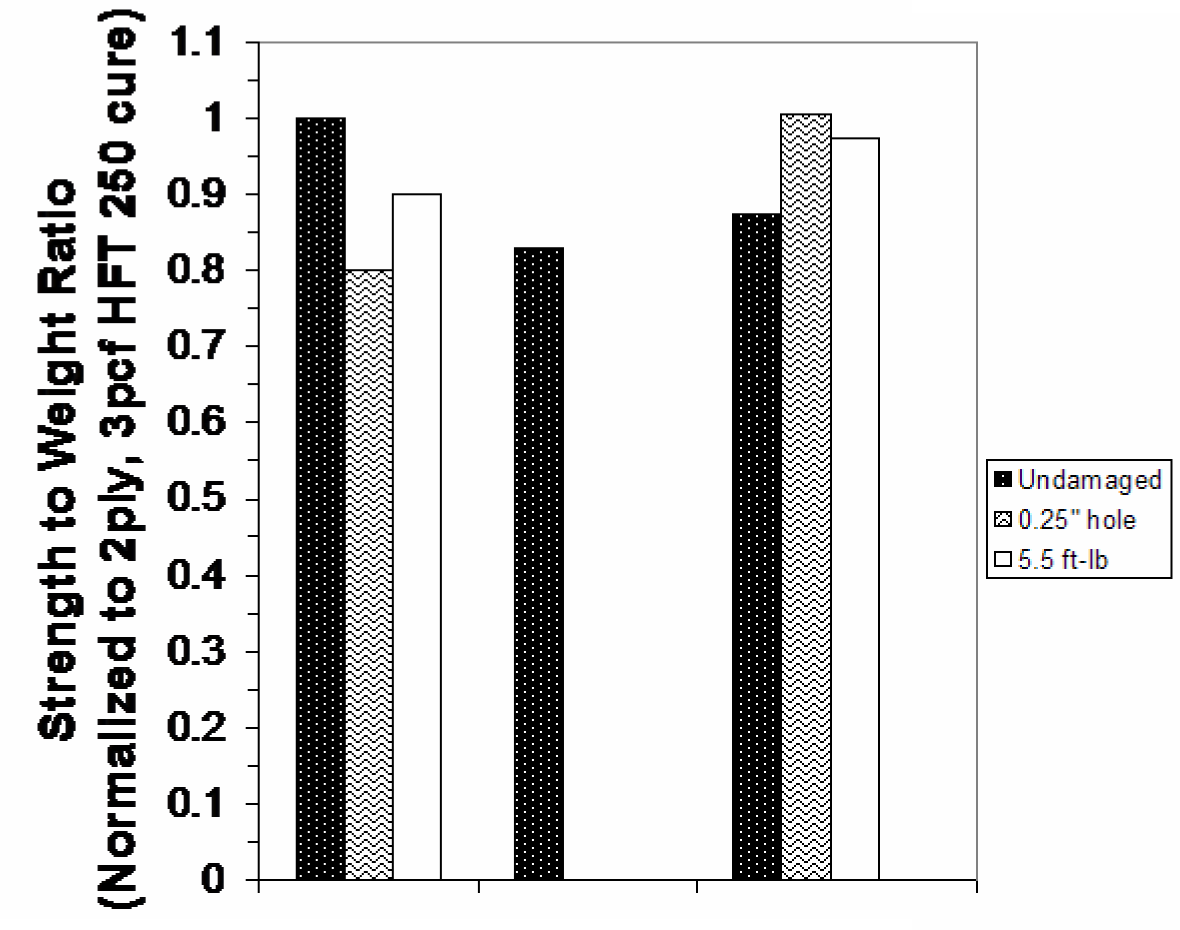


Strength/Weight ratio for various materials and layups (sandwich under compression)



0.25" hole <=> BVID

Strength/Weight ratio for different materials and layup (sandwich under shear)



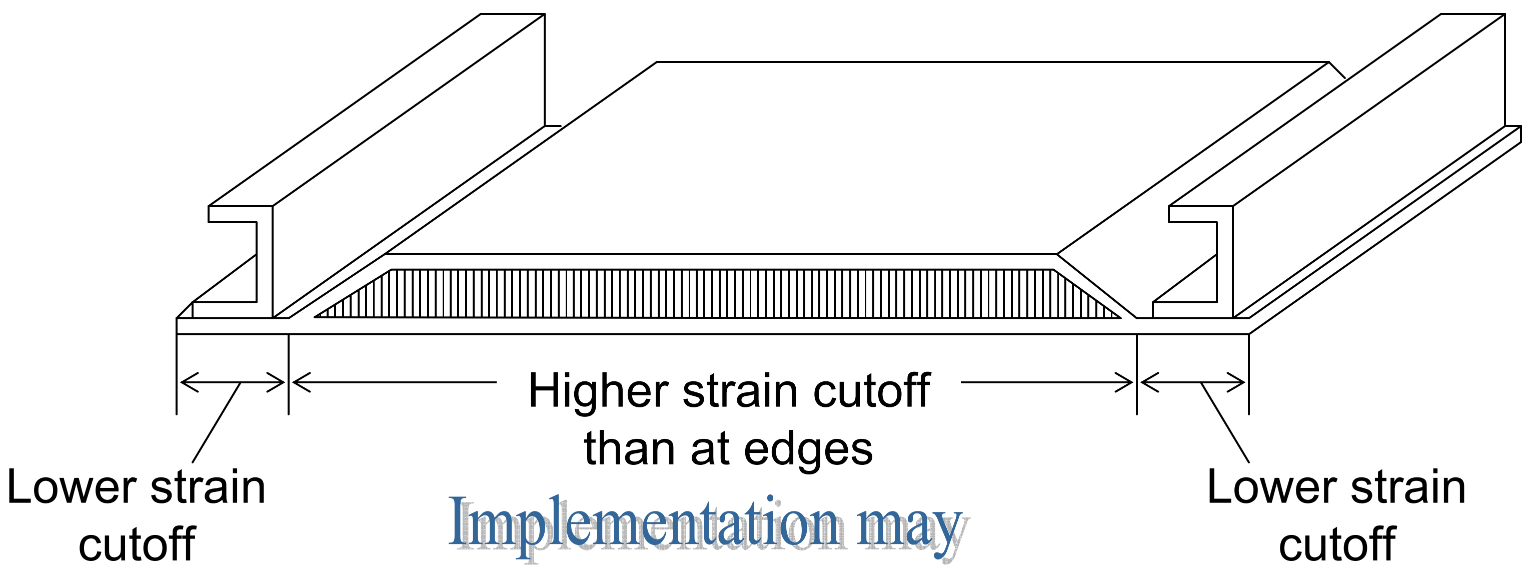
0.25" hole <=> BVID

BVID versus 0.25” hole (sandwich compression or shear)

- Statistically indistinguishable
- Can use 0.25” hole as a simpler test
- Can use hole analysis instead of more complicated impact damage analysis
- Subject to spot checking by tests (may be material dependent)

Cutoff strains

- Small coupon data are conservative
- Different cutoff strain values depending on application

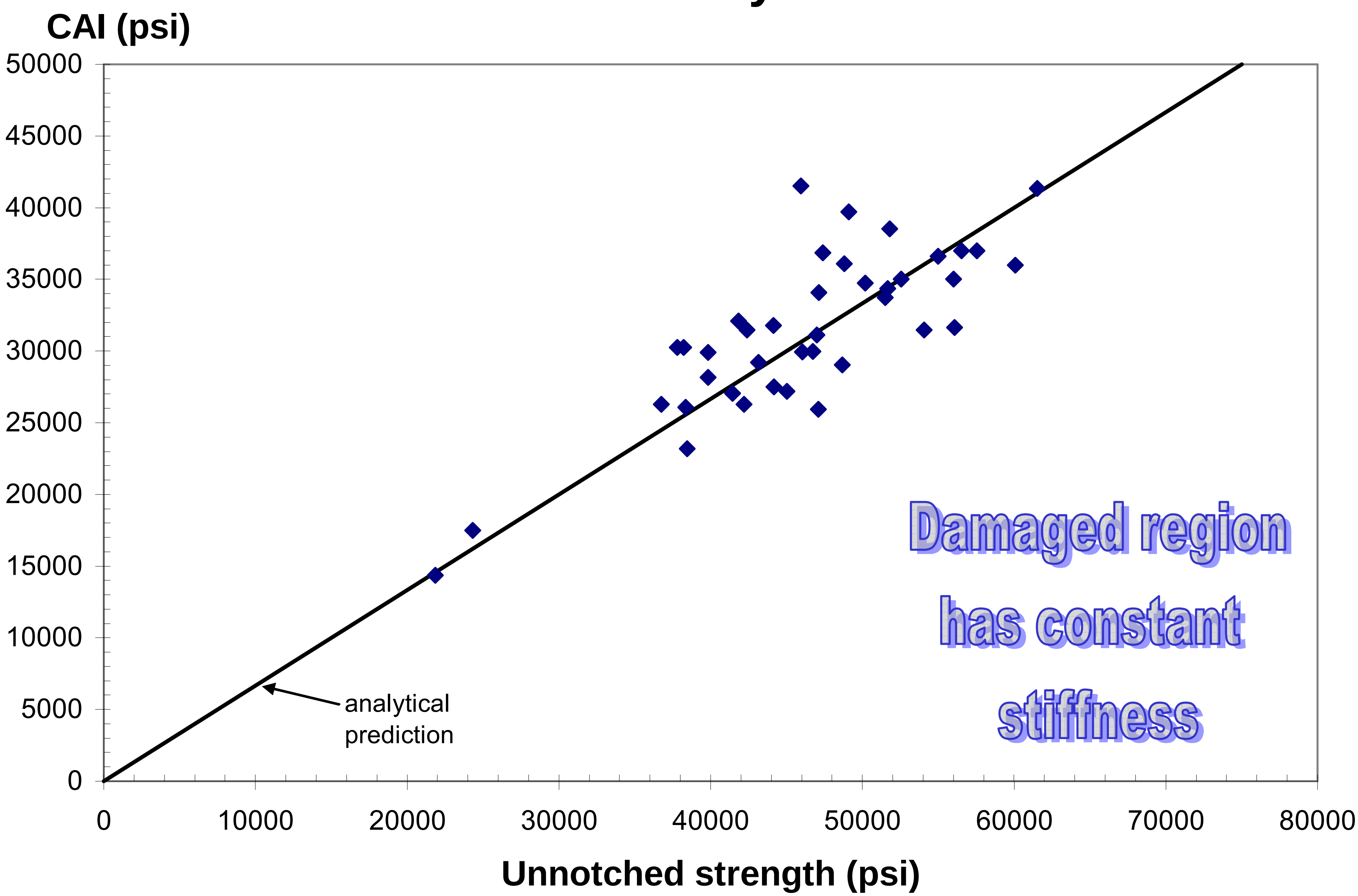


Implementation may require tailoring!

Modeling impact damage

- Area of reduced stiffness (modulus retention ratio concept)
- Lekhnitskii-based stress analysis for laminate with inclusion – constant stiffness in the damaged region
- Linear variation of stiffness in the damaged region – limited test input required
- ND tests to measure in-plane stiffness of damaged region very worthwhile

Sandwich CAI – Analysis versus test

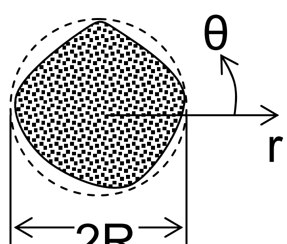


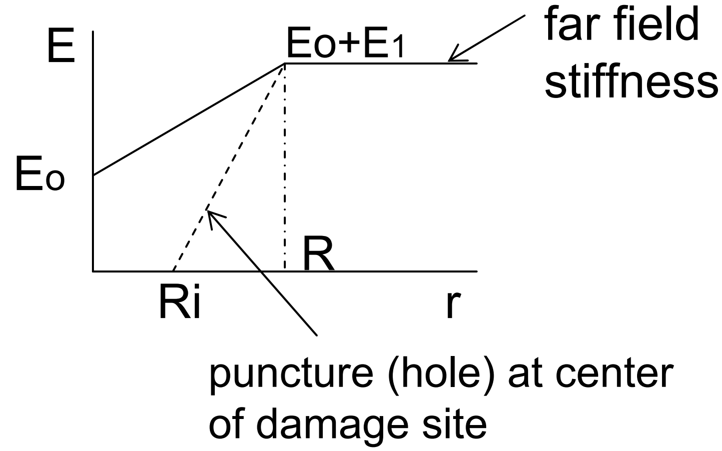
Improved CAI analysis

The approach [1] treats the site with impact damage as an inclusion of different stiffness.

The variation of the stiffness inside the damaged region as a function of the radial distance r (no dependence on θ),

$$E = E_o + E_1 \frac{r}{R}$$





- calculate average stiffness in damage region
- divide by far-field stiffness (modulus retention ratio)
- compute SCF:

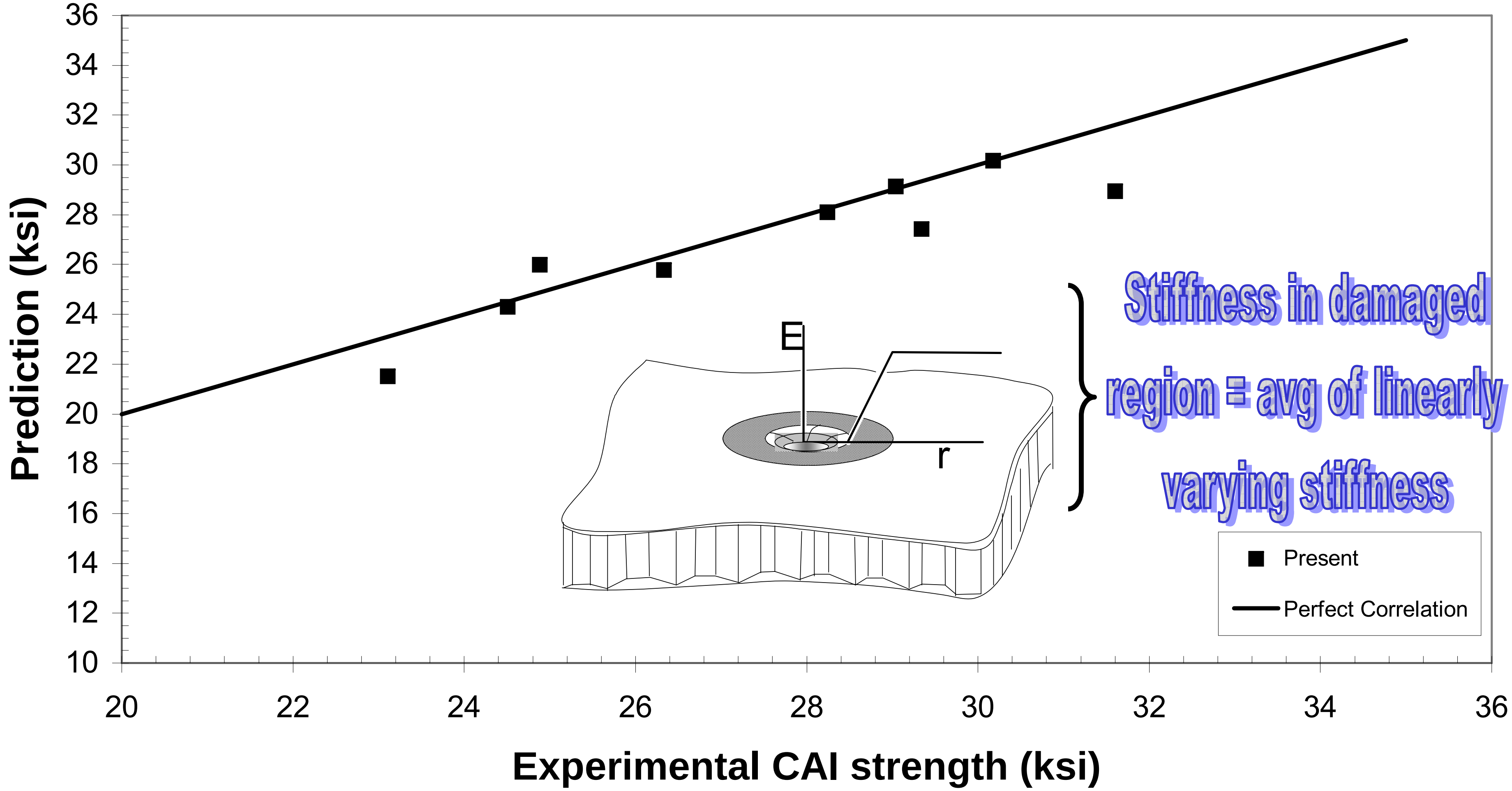
$$SCF = 1-(1-\lambda)\frac{1+\left(\lambda+(1-\lambda)\nu_{12}{}^{2}\dfrac{E_{22}}{E_{11}}\right)\sqrt{2\left(\sqrt{\dfrac{E_{11}}{E_{22}}}-\nu_{12}\right)+\dfrac{E_{11}}{G_{12}}}+\left(\dfrac{E_{11}}{G_{12}}-\nu_{12}\right)\sqrt{\dfrac{E_{22}}{E_{11}}}}{1+\lambda\left[\lambda+\left(1+\sqrt{\dfrac{E_{22}}{E_{11}}}\right)\sqrt{2\left(\sqrt{\dfrac{E_{11}}{E_{22}}}-\nu_{12}\right)+\dfrac{E_{11}}{G_{12}}}\right]+\left(\dfrac{E_{11}}{G_{12}}-2\lambda\nu_{12}\right)\sqrt{\dfrac{E_{22}}{E_{11}}}-(1-\lambda)^{2}\nu_{12}{}^{2}\dfrac{E_{22}}{E_{11}}}$$

- calculate CAI strength:

$$\sigma_{CAI} = \frac{\sigma_u}{SCF}$$

Ideally, should create a model that predicts Eo, E1 using NDI data. If not available, constants Eo and E1 can be back-calculated from one specimen and applied to other energy levels. R is measured from one specimen; Ri, if non-zero, assuming linear variation of Eo/(Eo+E1) and the same test specimen

CAI predictions versus test – improved model



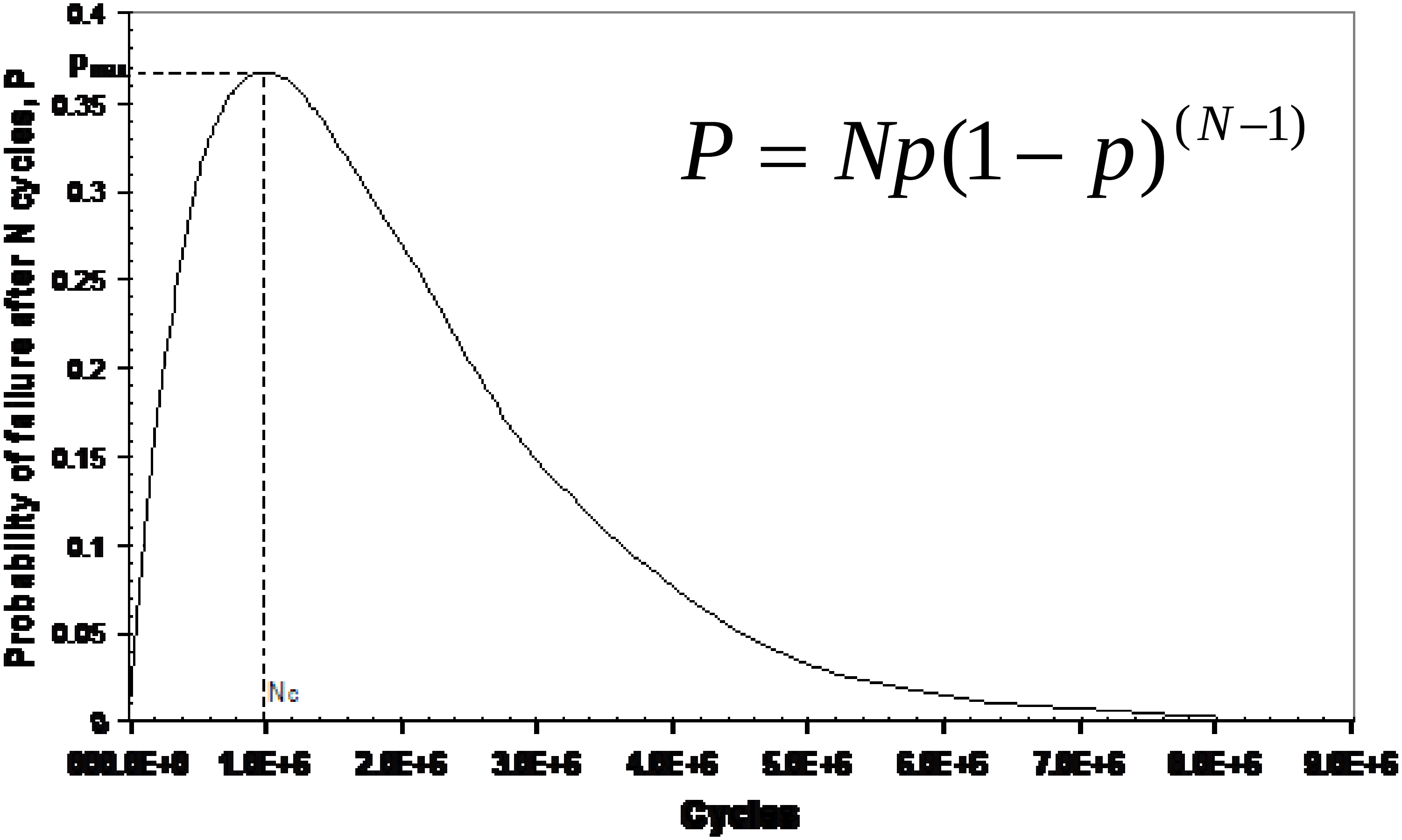
Fatigue analysis (sandwich or monolithic structure)

- Probability of failure p during each cycle
- Probability of failure P after n cycles
- Maximizing P as a function of cycles gives a prediction for the cycles to failure
- p ? In simplest approach assume p=const
- Obtain p from static test data (statistical distribution for static strength gives p)

Fatigue analysis

- R ratio dependence
- Statistical distribution dependence (normal versus 2-parameter Weibull)
- Sensitivity to statistical parameters (scatter)

Fatigue analysis based on the probability of failure



$$P = Np(1-p)^{(N-1)}$$

Cycles to failure

$$N_c = -\frac{1}{\ln(1-p)}$$

$$p = 1 - 0.5\left[1 - \left[1 + \left(A + BZ_p\right)^C\right]^D + \left[1 + \left(A - BZ_p\right)^C\right]^D\right]$$

$$Z_p = \frac{\left|\sigma_{\max} - X_m\right|}{s}$$

$$A = 0.644693$$

$$B = 0.161984$$

$$C = 4.874$$

$$D = -6.158$$

Normal distribution

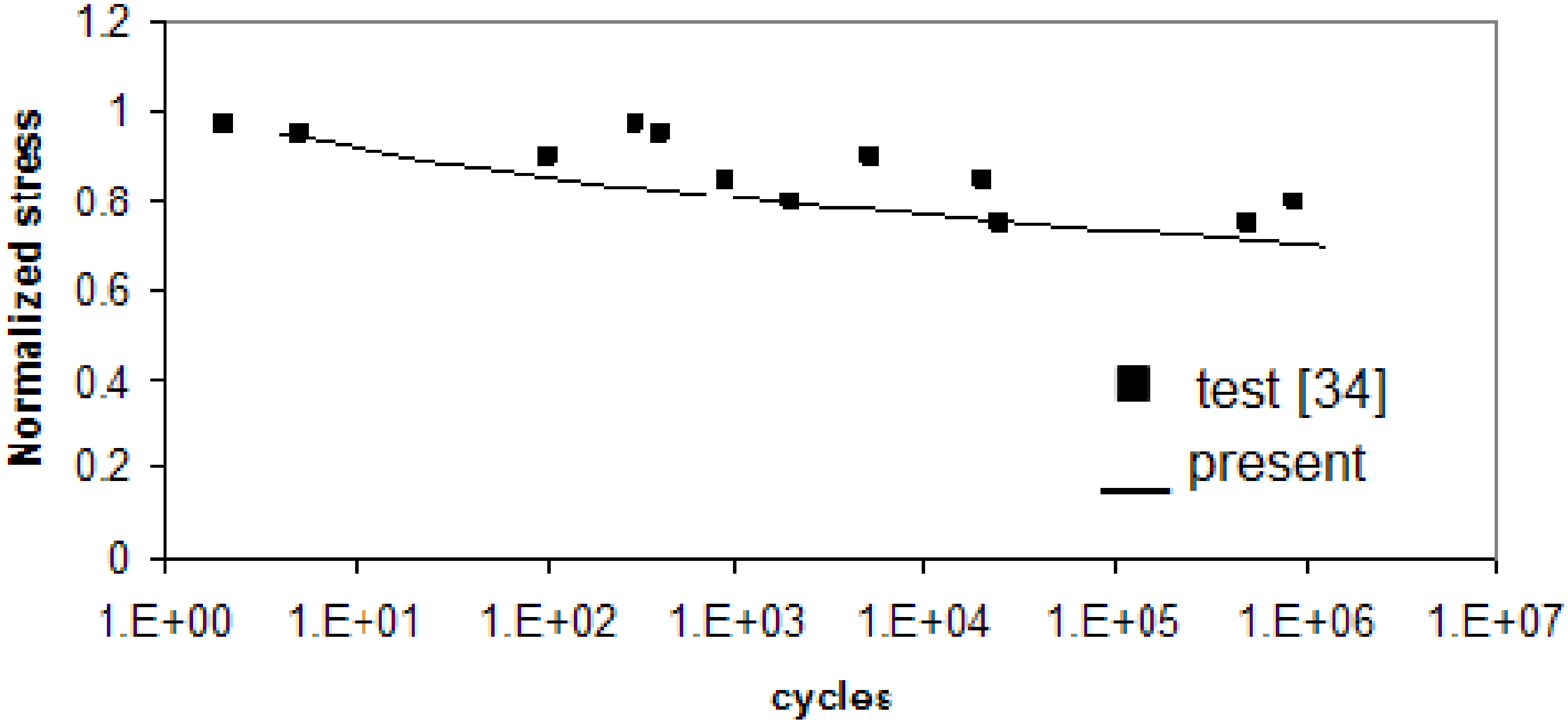
$$\sigma_{\max} = \beta\left(\frac{1}{N_f}\right)^{\left(\frac{1}{\alpha}\right)}$$

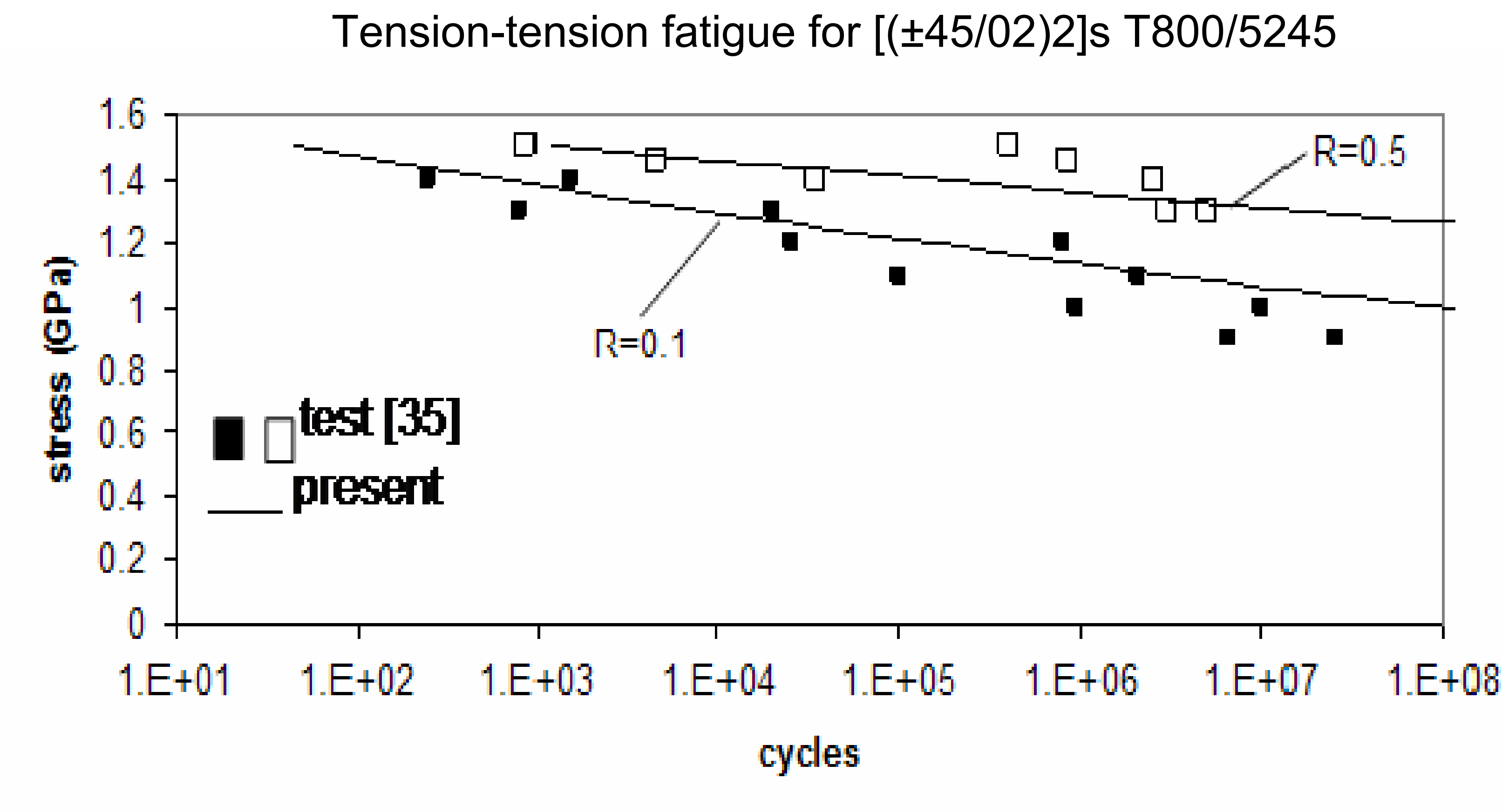
2 par Weibull with

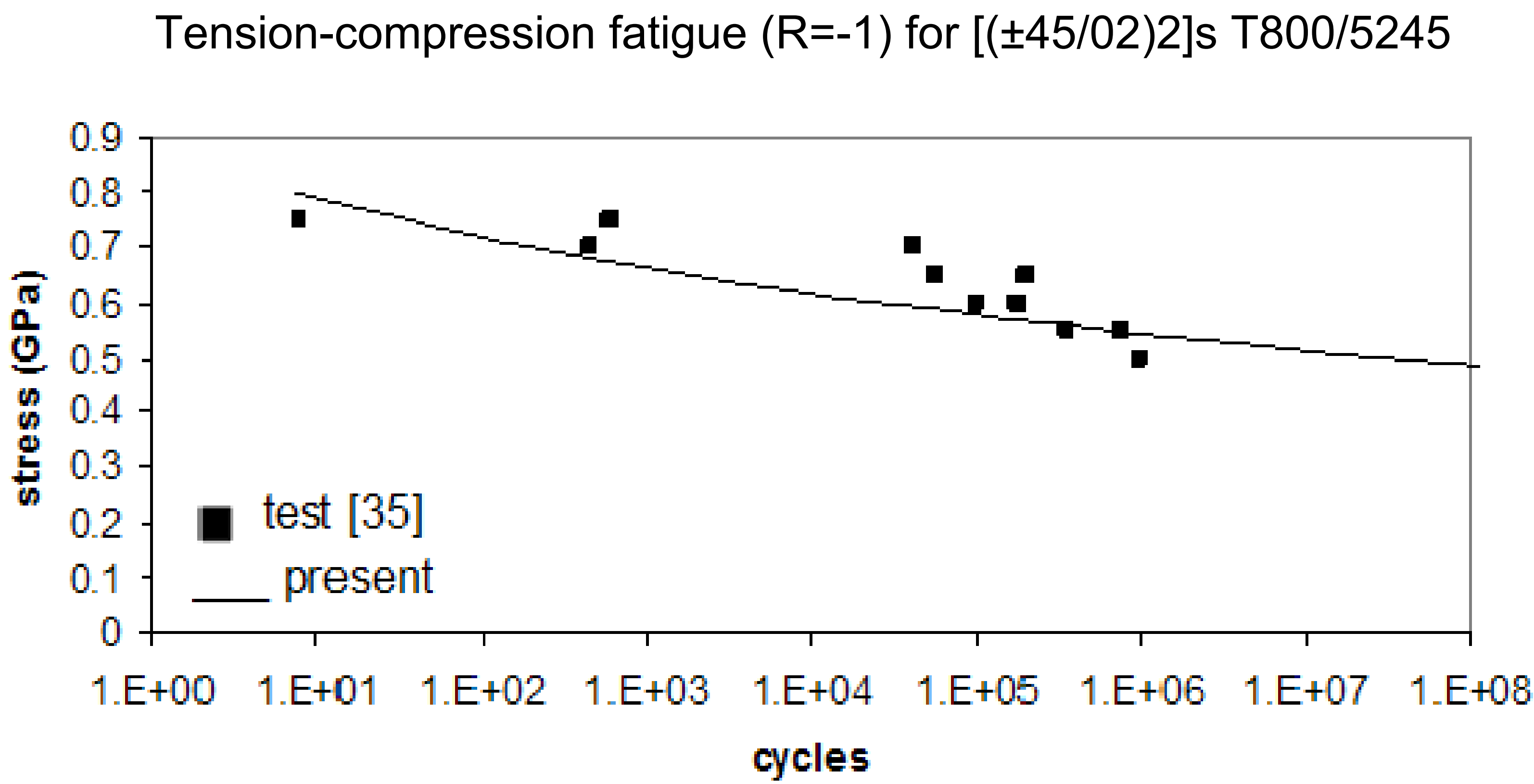
α shape parameter and

β scale parameter

Unidirectional AS4/3501-6 with R=0.

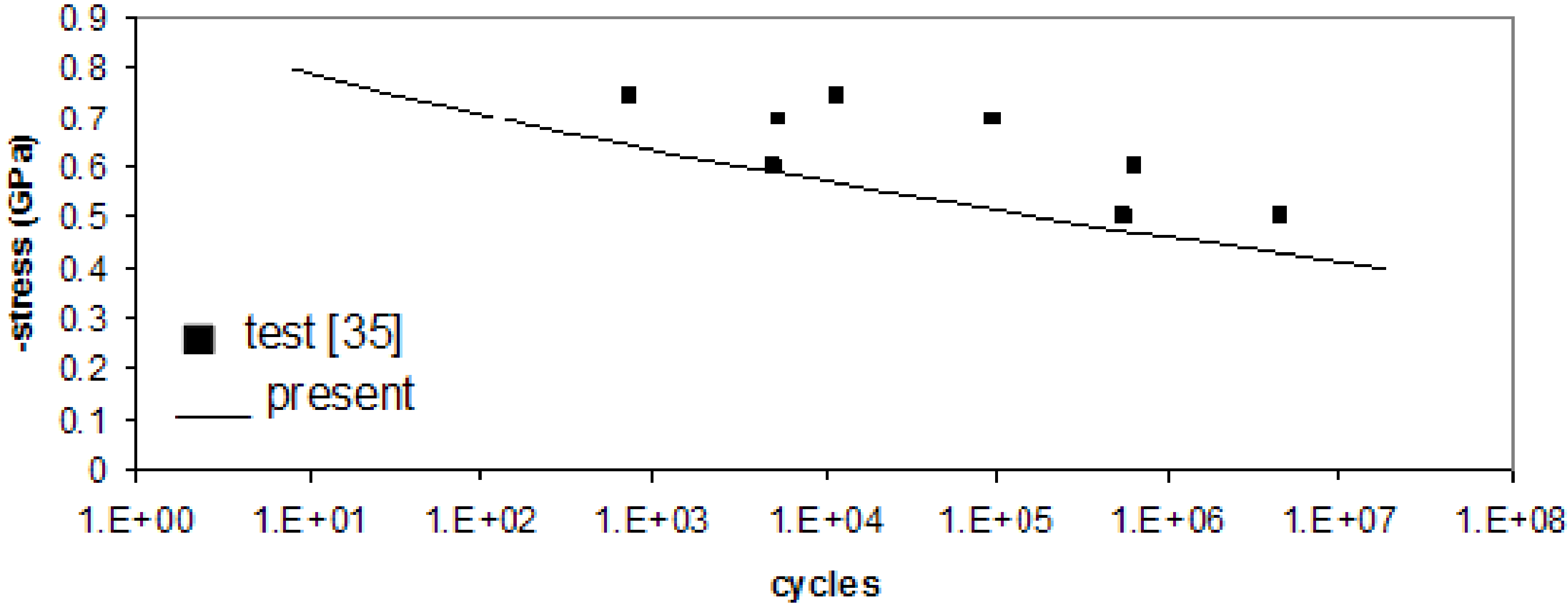



Tension-tension fatigue for [(±45/02)2]s T800/5245
stress (GPa)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.E+01
1.E+02
1.E+03
1.E+04
1.E+05
1.E+06
1.E+07
1.E+08
cycles
R=0.5
R=0.1
test [35]
present

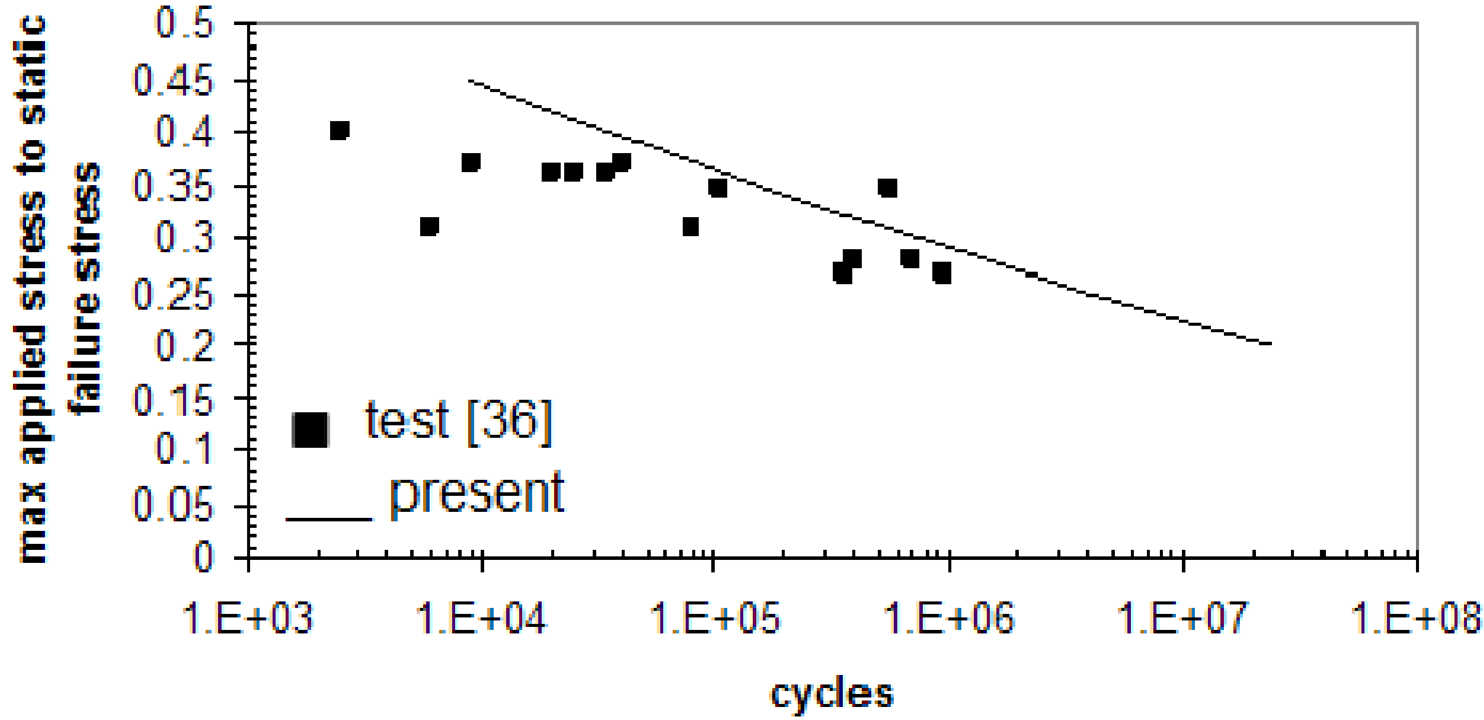


Tension-compression fatigue (R=-1) for [(±45/02)2]s T800/5245
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
stress (GPa)
test [35]
present
1.E+00
1.E+01
1.E+02
1.E+03
1.E+04
1.E+05
1.E+06
1.E+07
1.E+08
cycles

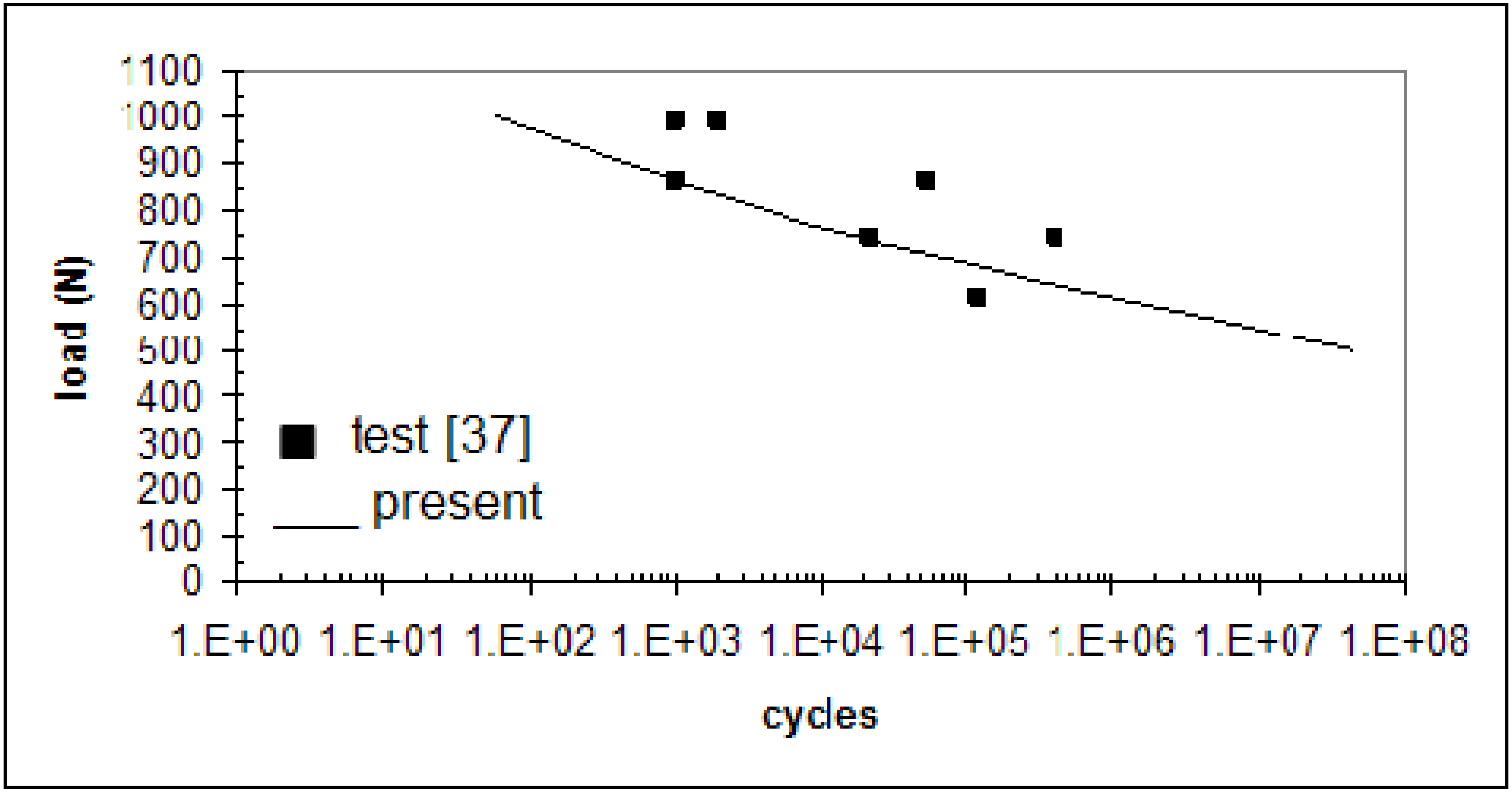
Compresion-compression fatigue **(R=10)** for [(±45/02)2]s T800/5245



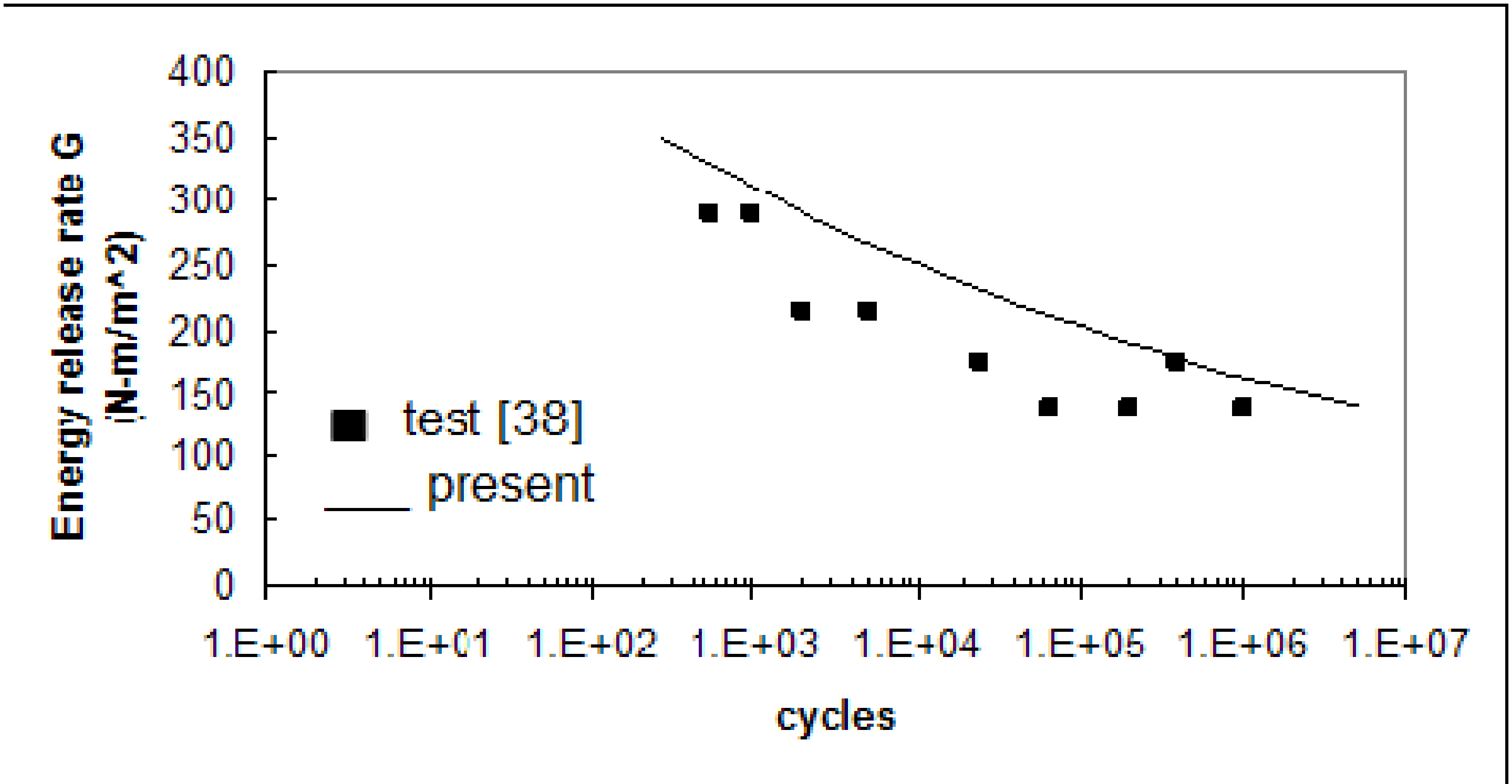
Tension-Torsion case (tension=torsion and R=0) for woven glass fabric



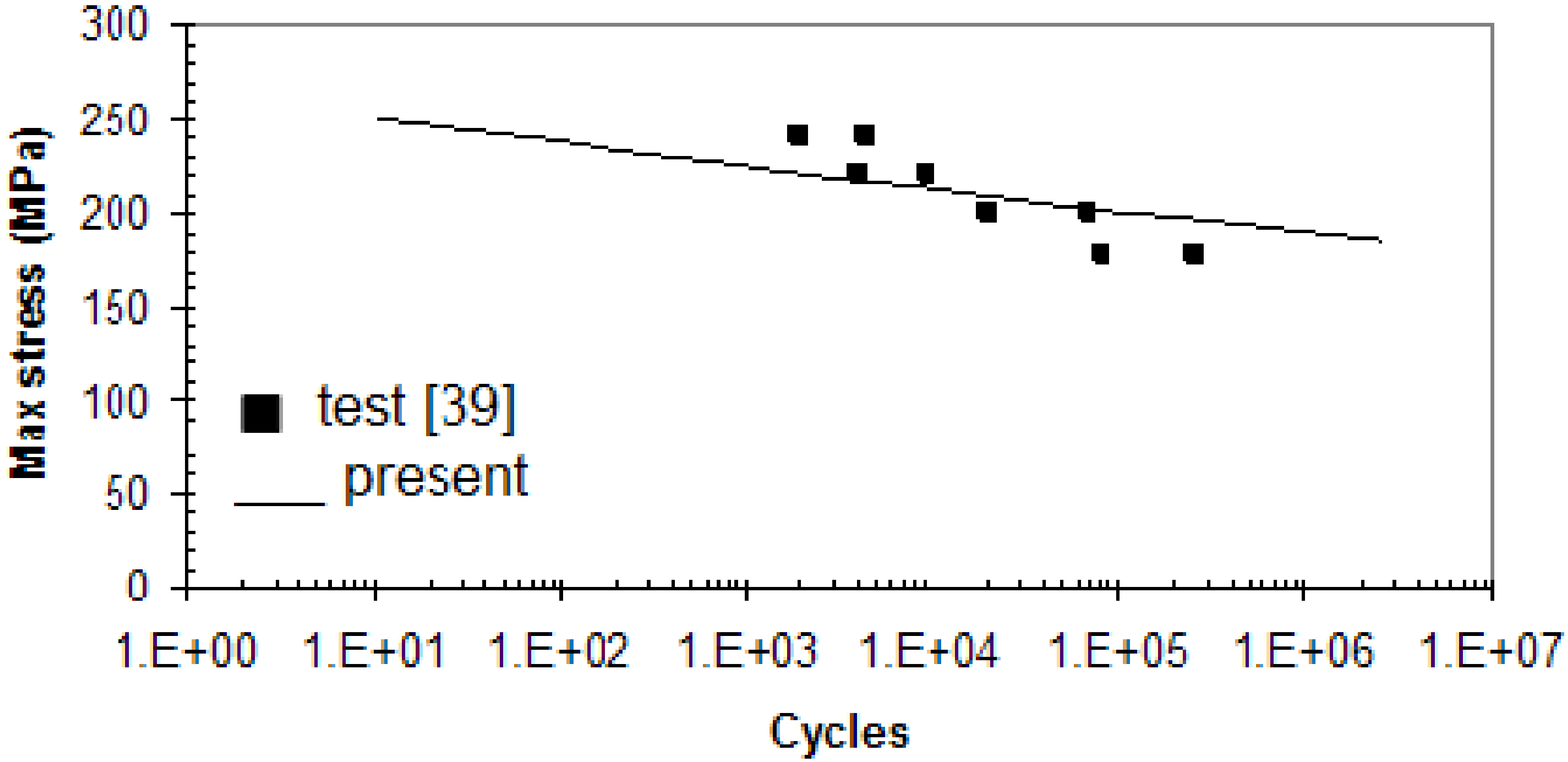
Onset of delamination load for skin/stiffener configuration (R=0.1, IM6/3501-6 material)



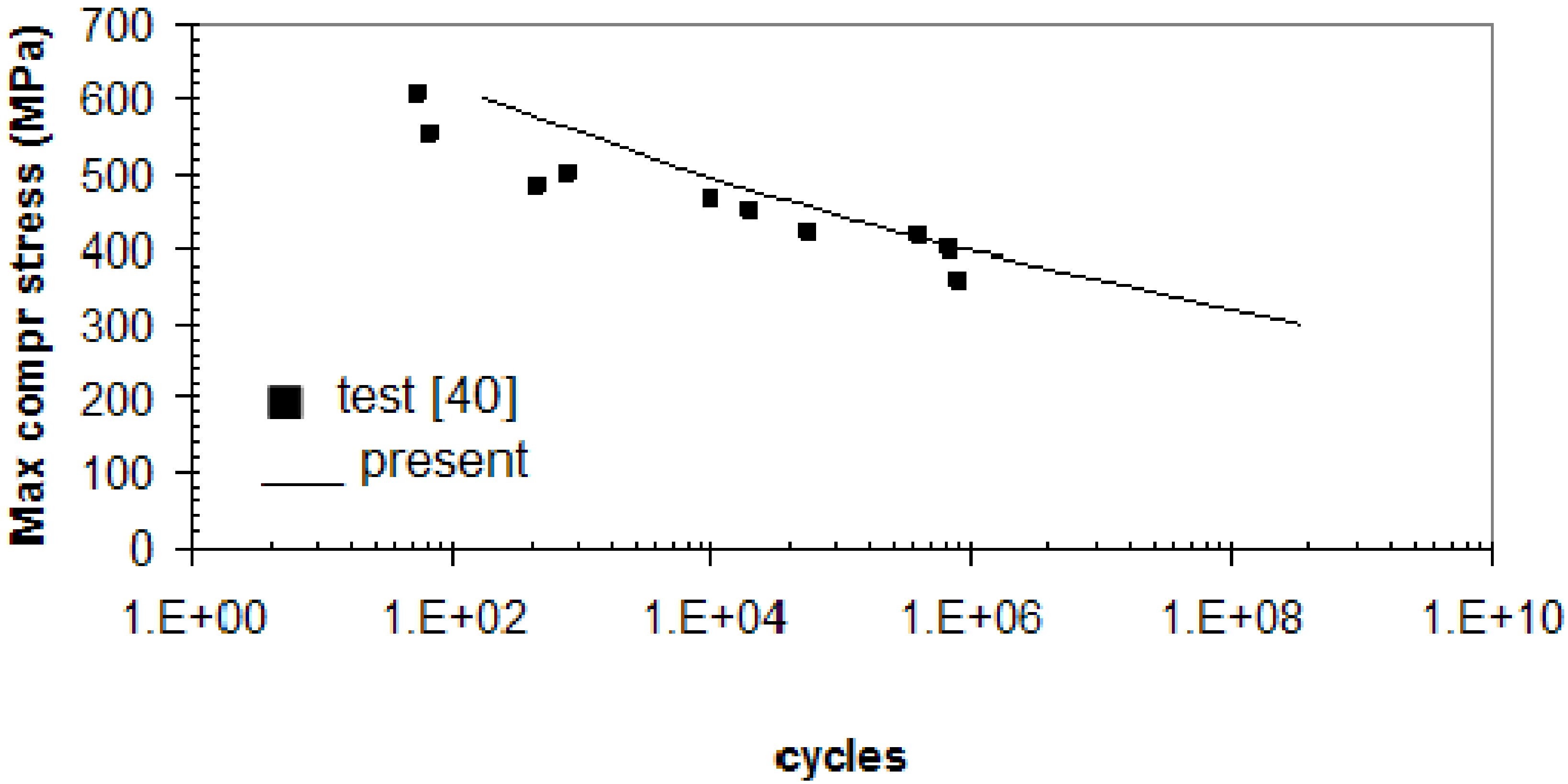
. Onset of edge delamination for [35_2/-35_2/0_2/90_2]s AS4/PEEK (R=0.1)

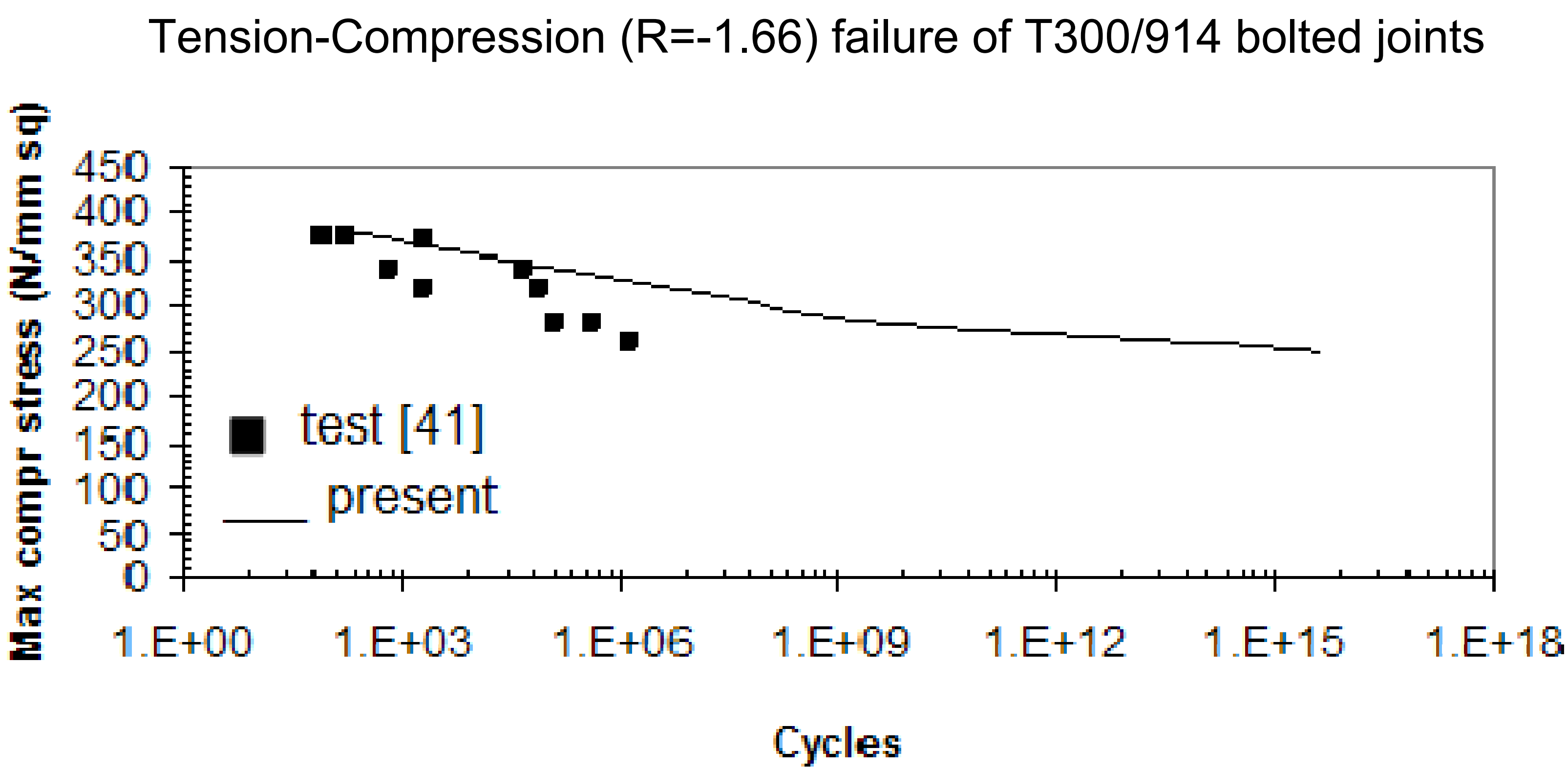


Onset of delamination for quasi-isotropic glass/epoxy (R=0.1)

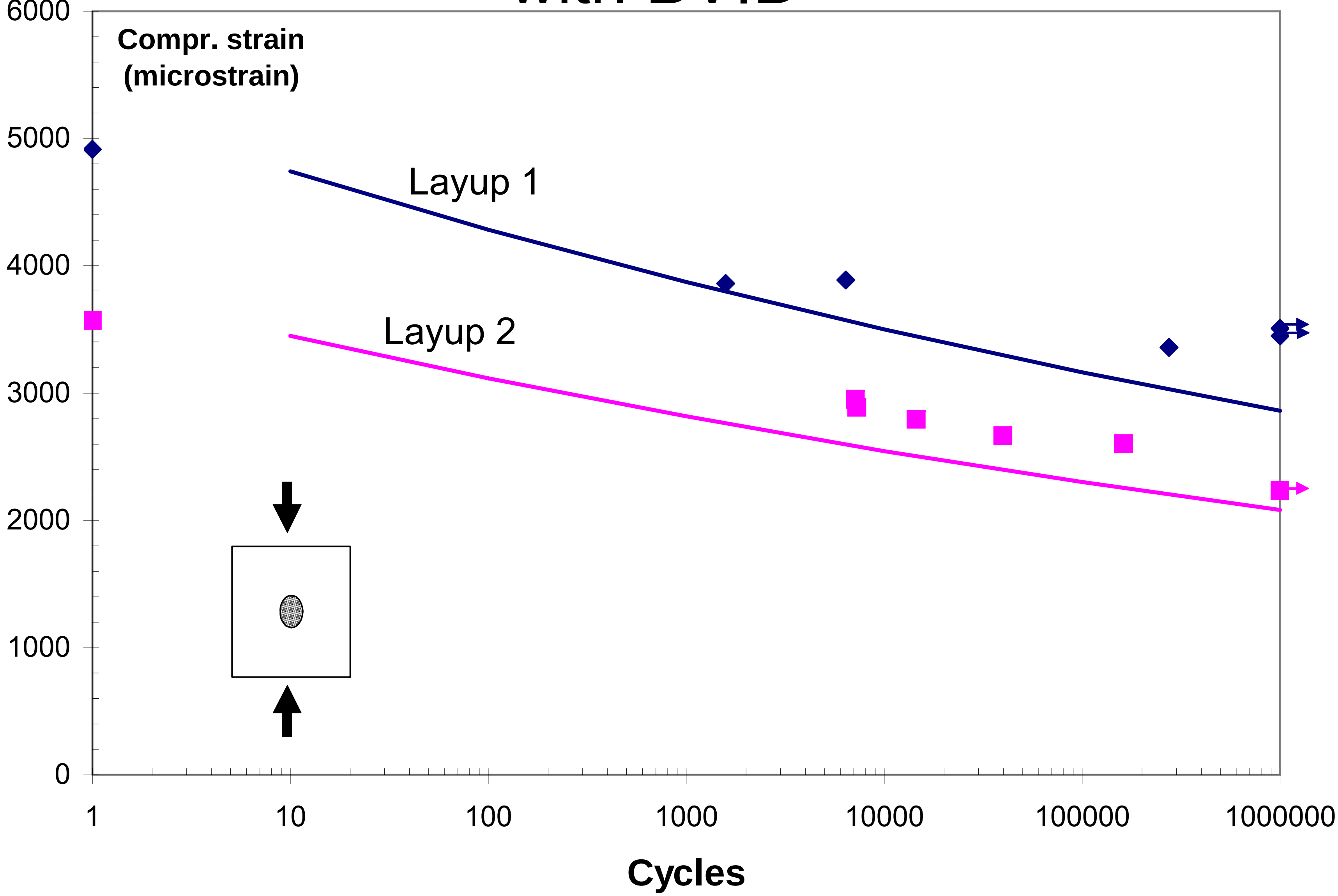


Tension-compression fatigue (R=-1) of [02/±45/02/±45/90]s BMI laminate




Tension-Compression (R=-1.66) failure of T300/914 bolted joints
Max compr stress (N/mm sq)
450
400
350
300
250
200
150
100
50
0
test [41]
present
1.E+00
1.E+03
1.E+06
1.E+09
1.E+12
1.E+15
1.E+18
Cycles

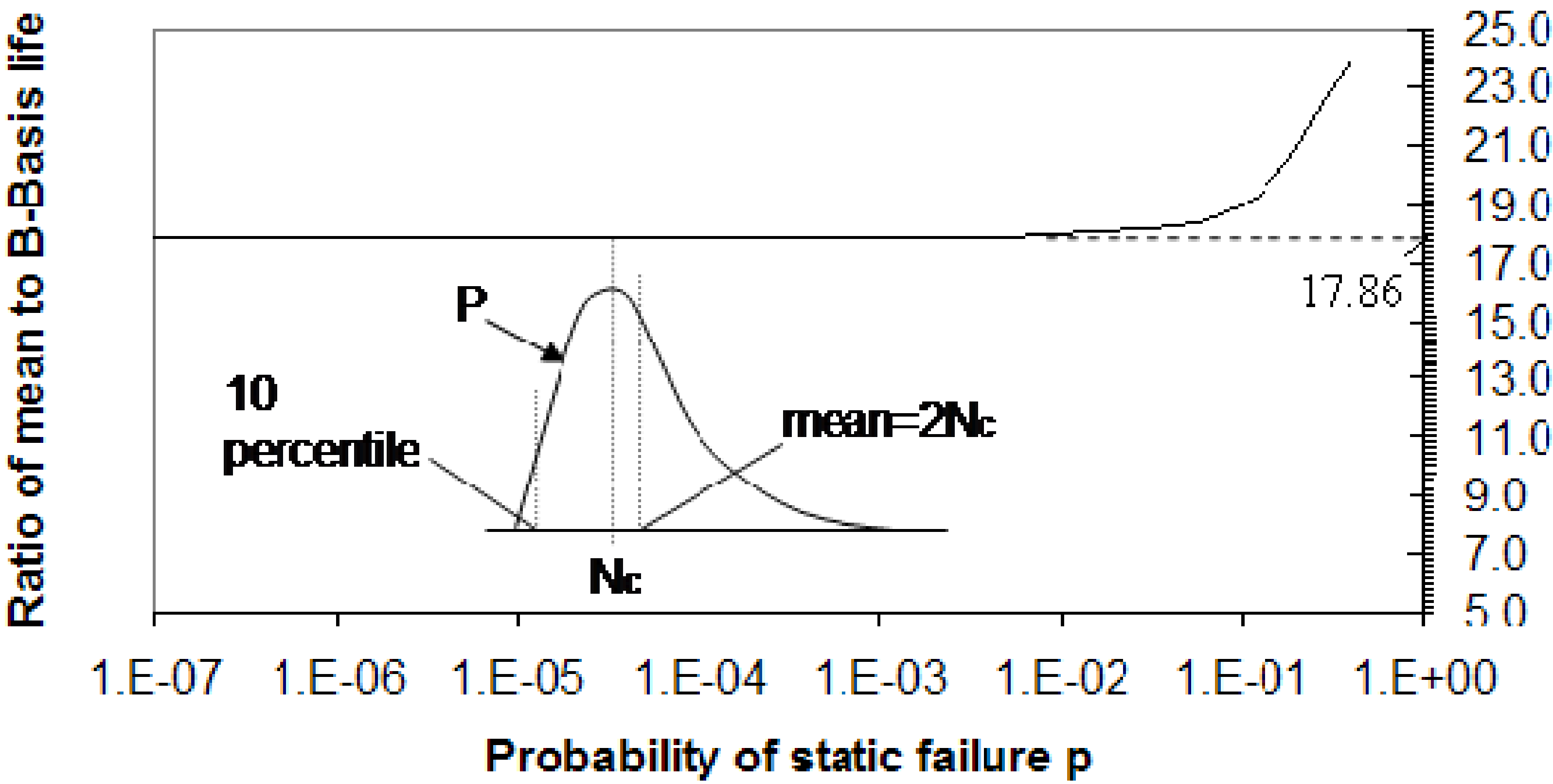
Fatigue predictions for sandwich specimens with BVID



Applications

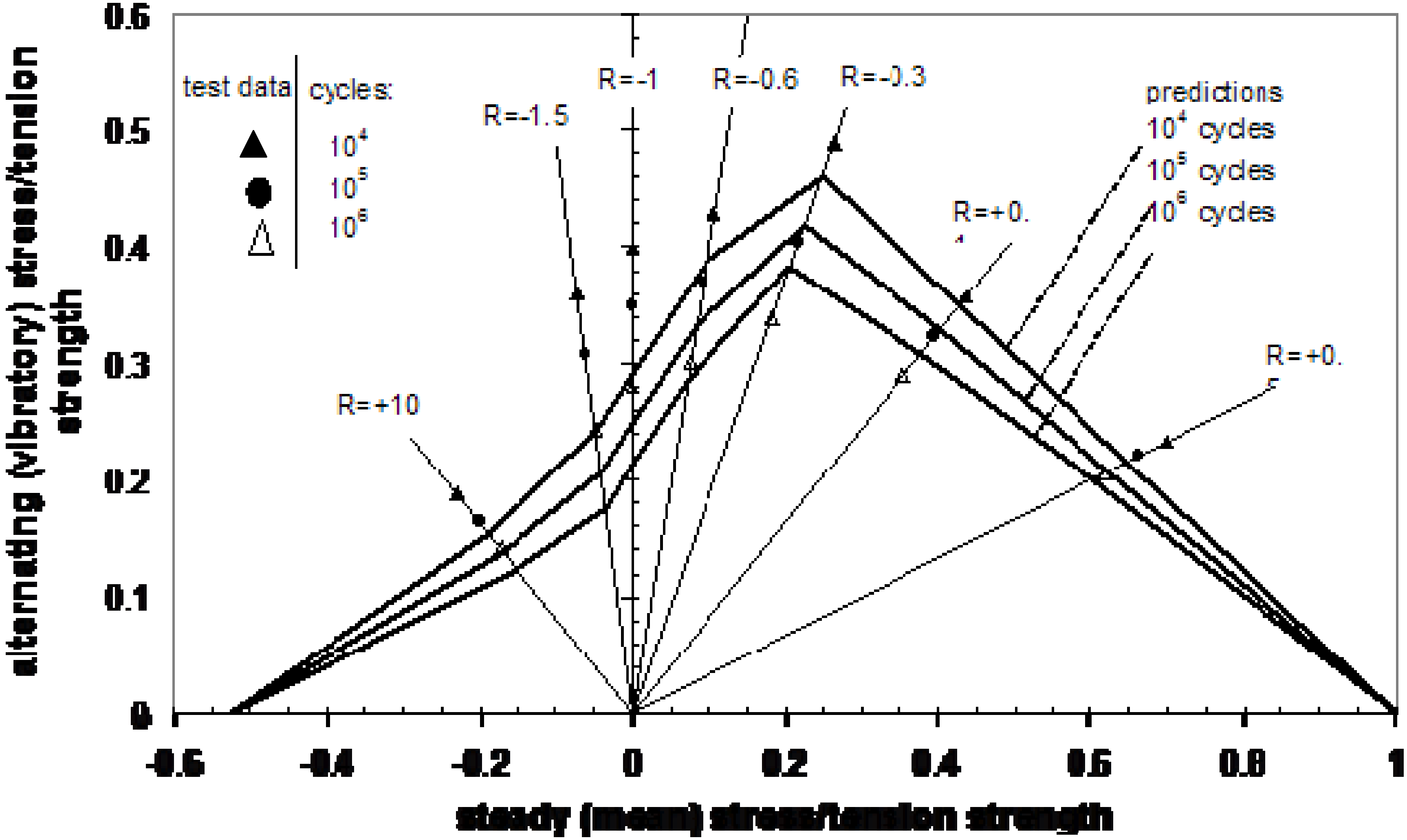
- Fatigue life prediction under constant amplitude
- Determination of B- (or A-) Basis life curve
- “Goodman” diagrams
- Truncation levels for testing
- Extension to spectrum loading

Determination of B-Basis life

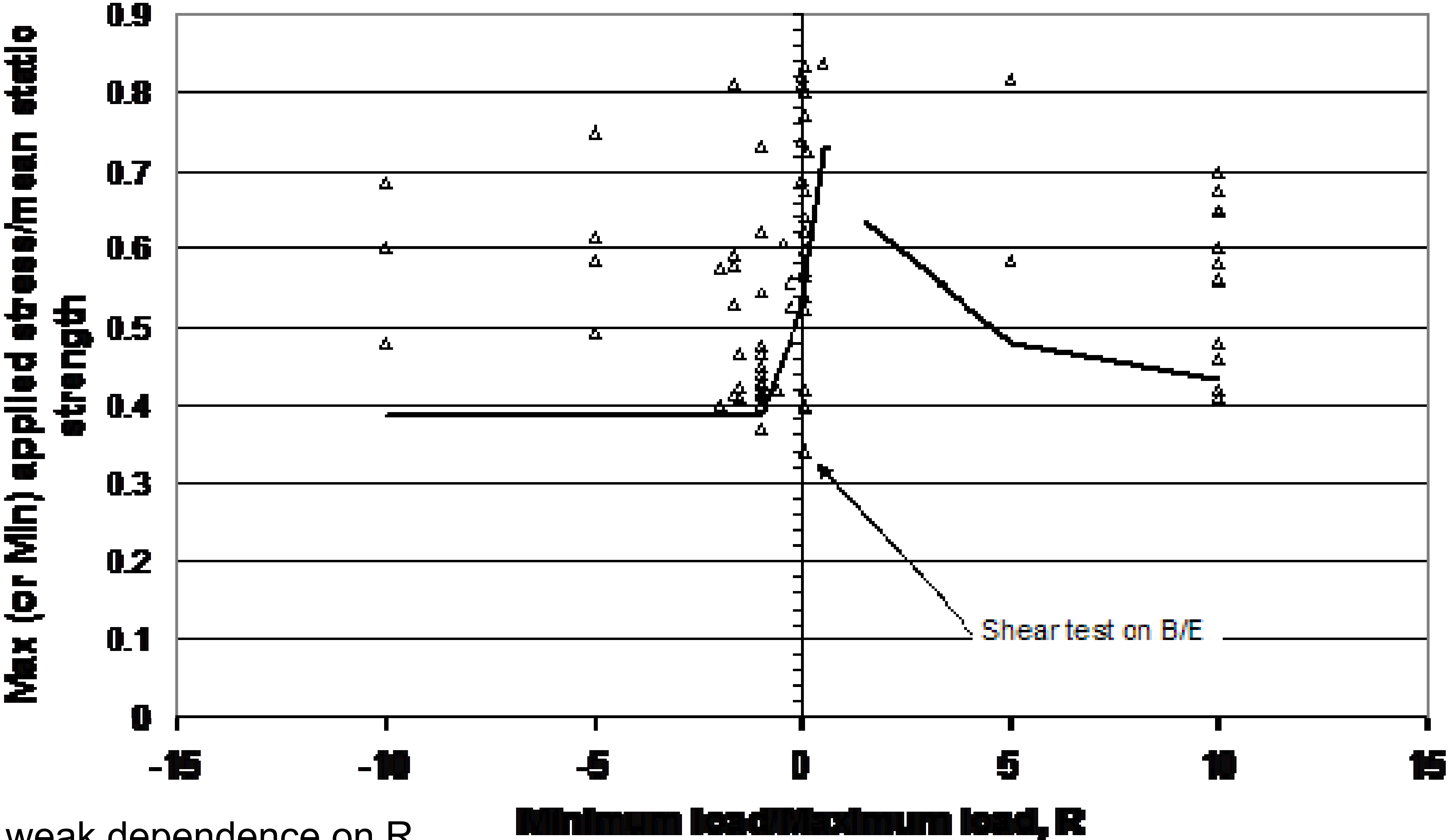


- compare to Northrop report value of 13

“Goodman” diagram



Truncation level determination



- weak dependence on R
- 0.3-0.4 for 1 million cycles

Reminder

- still need to account for environment, material scatter (if not explicitly included in equations)

Conclusions

- 0.25" holes and BVID damage for sandwich are equivalent (compression and shear)
- predictions for CAI for sandwich with BVID
- determination of cycles to failure under constant amplitude
- application to:
  - B-Basis life determination
  - Goodman diagrams
  - truncation levels

Caveats

- Hole to Impact equivalence is a function of
  - specimen size
  - maybe material(?)
- Determination of fatigue curves requires further improvements:
  - Non constant value of p (track damage creation and growth)
  - Improved methodology for R-dependence
- "Analysis without testing is almost as bad as testing without analysis"