Glass Performance Days 2025

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GLASS PERFORMANCE DAYS 2025

STRUCTURAL ANALYSIS OF LAMINATED GLASS WITH EVA UNDER OUT-OF-PLANE LOADING AND CORRELATION BETWEEN ANALYTICAL, NUMERICAL AND EXPERIMENTAL RESULTS

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INTRODUCTION

- Comparison of analytical results with numerical and experimental results
- The aim is to reduce the reliance on extensive and costly experimental testing
- For laminated glass, bending stress and deflection can be determined analytically by using the “effective thickness” method

- CEN EN 16612 (2019)
- CEN/TS 19100-2 (2021)
- Enhanced Effective Thickness method (Galuppi and Royer-Carfagni 2012)
- Wölfel-Bennison approach (Calderone et al. 2009)

METHODOLOGY

- Structural analyses of laminated glass with EVA interlayer
- Comparison of analytical, numerical and experimental results for the simple statically determined model in the intact state
- Behaviour of laminated glass with EVA interlayer at the room temperature, under out-of-plane loading, prior to breakage of glass ply

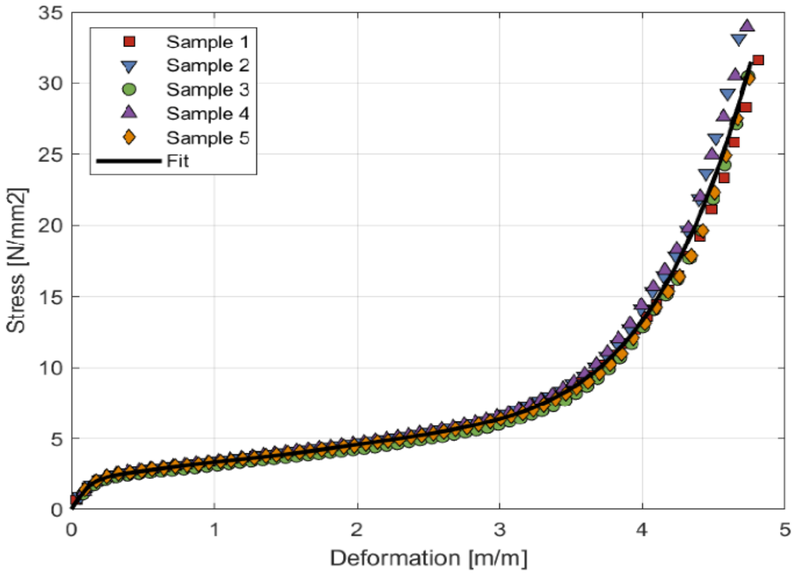
NUMERICAL MODEL

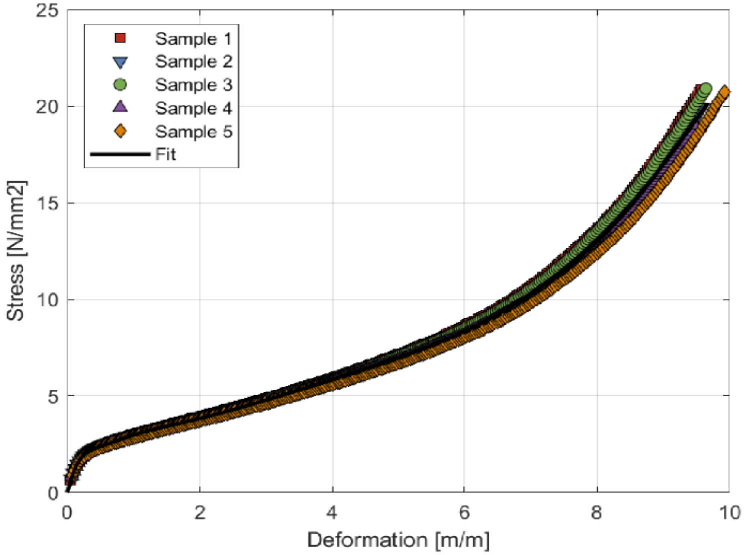
– Ansys model
– thickness of glass plies is $h = 4/6/10mm$
– 0.76/0.89/1.52 mm thick EVA interlayer.
– the span and width of the element is 1000 mm x 360 mm

Non-linear Mooney-Rivlin 9-parameter model using a defined mathematical function

The first part of stress-strain functions is defined with Young's modulus $E_1 = 16.8MPa$ and $E_2 = 12MPa$ and the non-linear part

EVA 1 and EVA 2 experimental data and model fit





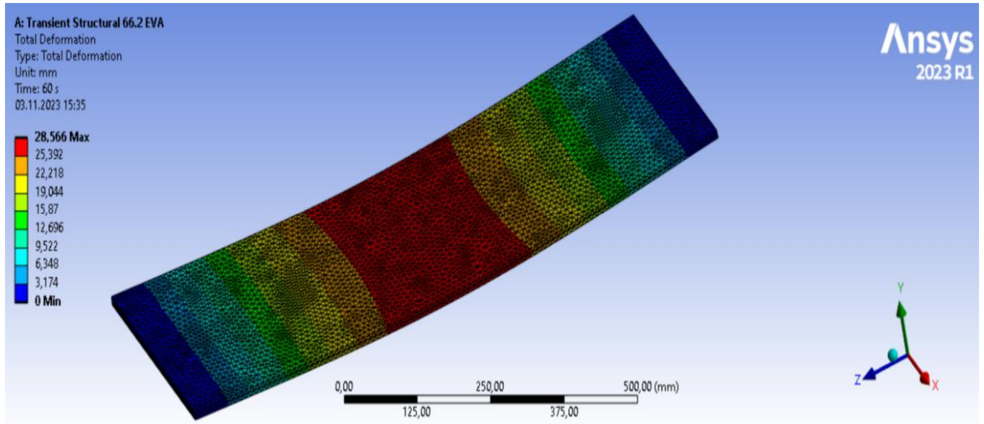
Basic mechanical properties of glass according to CEN EN 16612 (2019)

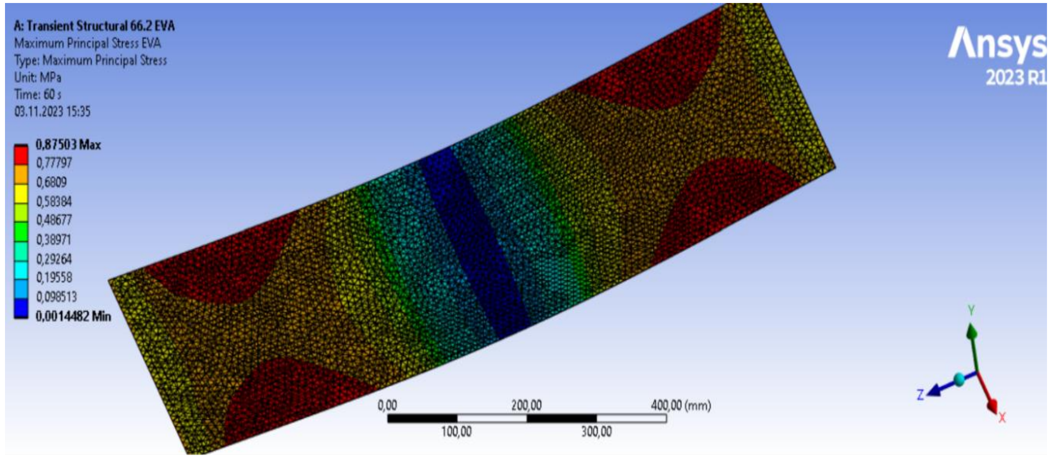
Properties	Middle value	Interval
Glass density	ρ = 2500 kg/m^3	2250 – 2750 kg/m^3
Young's modulus	E = 70 000 MPa	63 000 – 77 000 MPa
Poisson number	μ = 0.23	0.20 – 0.25

Characteristic bending strength of each type of glass according to CEN EN 16612 (2019)

Annealed glass/Float glass	Heat-strengthened glass (HSG)	Thermally toughened glass (TTG)
45 N/mm^2	70 N/mm^2	120 N/mm^2

Contact between glass and interlayer is defined as a full bond.





Deformation for VSG ESG 66.2 (0.76 mm) intact state with EVA for the load of 5 kN

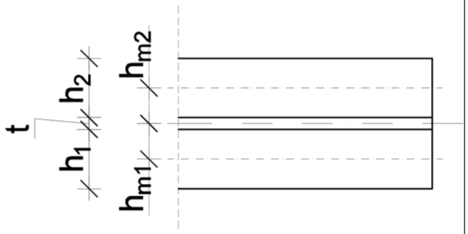
EVA stress response for the load of 5 kN

Analytical calculation – Effective thickness approach

CEN EN 16612 (2019)

$$h_{ef,w} = \sqrt[3]{\sum_k h_k^3 + 12\omega\left(\sum_k h_k h_{m,k}^2\right)} \quad (1)$$

$$h_{ef,\sigma,j} = \sqrt{\frac{h_{ef,w}^3}{h_j + 2\omega h_{m,j}}} \quad (2)$$



ω - the shear transfer coefficient depending on the type of interlayer that is used and the loading case

$h_{ef,w}$ - the effective thickness for calculating the deflection of any glass ply in the panel

$h_{ef,\sigma,j}$ - the effective thickness for normal stress calculation of j-th glass ply

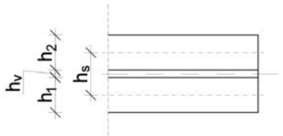
h_k and h_j - the thicknesses of the individual glass plies

$h_{m,k}$ and $h_{m,j}$ - the distances of the mid-pane of the k-th or j-th glass plies from the mid-pane of the laminated glass

Analytical calculation – Effective thickness approach

Wölfel-Bennison approach

$h_{ef,w} = \sqrt[3]{h_1^3 + h_2^3 + 12 \cdot \Gamma \cdot I_s}$	(3)
$h_{ef,\sigma,1} = \sqrt{\dfrac{h_{ef,w}^3}{h_1 + 2 \cdot \Gamma \cdot h_{s,2}}}$	(4)
$\Gamma = \dfrac{1}{1 + \beta \cdot \dfrac{E \cdot I_s \cdot h_v}{G \cdot {h_s}^2 \cdot a^2}}$	(5)



$h_{ef,w}$ - the effective thickness for calculating the deflection of any glass ply in the panel

$h_{ef,\sigma,j}$ - the effective thickness for normal stress calculation of j-th glass ply

Γ- the shear transfer coefficient defined in (5)

G – interlayer shear modulus

E – Youngs modulus for glass

a - shortest bending direction - span

$I_s = h_1 \cdot {h_{s,2}}^2 + h_2 \cdot {h_{s,1}}^2$

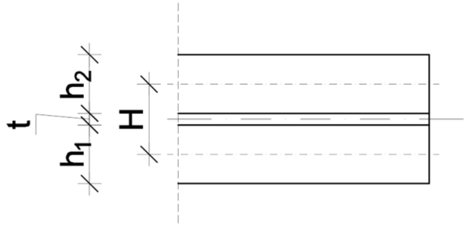
$h_{s,1} = \dfrac{h_s \cdot h_1}{h_1 + h_2}; \; h_{s,2} = \dfrac{h_s \cdot h_2}{h_1 + h_2}$

$h_s = 0.5 \cdot (h_1 + h_2) + h_v$

Analytical calculation – Effective thickness approach

Enhanced Effective Thickness method by Galuppi and Royer-Carfagni (2012)

$h_{ef,w} = \dfrac{1}{\sqrt[3]{\dfrac{\eta}{h_1^3 + h_2^3 + 12I_s} + \dfrac{1-\eta}{h_1^3 + h_2^3}}}$	(6)
$h_{1,ef,\sigma} = \dfrac{1}{\sqrt[3]{\dfrac{2\eta h_{s,2}}{h_1^3 + h_2^3 + 12I_s} + \dfrac{h_1}{h_{ef,w}{}^3}}}$	(7)
$h_{2,ef,\sigma} = \dfrac{1}{\sqrt[2]{\dfrac{2\eta h_{s,1}}{h_1^3 + h_2^3 + 12I_s} + \dfrac{h_2}{h_{ef,w}{}^3}}}$	(8)
$\eta = \dfrac{1}{1 + \dfrac{I_1 + I_2}{\mu \cdot I_{tot}} \cdot \dfrac{A_1 \cdot A_2}{A_1 + A_2} \Psi}$	(9)



h_1 and h_2 - the thickness of the glass plies

I_s - the “bonding inertia”

η - the coupling parameter depending on the shear stiffness of the interlayer, loading, and boundary conditions defined in (9)

$h_{s,1}$ and $h_{s,2}$ - modified dimensions of the cross-section

Ψ – coefficient depending on geometry of the beam, boundary and loading condition

G – interlayer shear modulus

E – Youngs modulus for glass

I_1 – moment of inertia for ply 1

I_2 – moment of inertia for ply 2

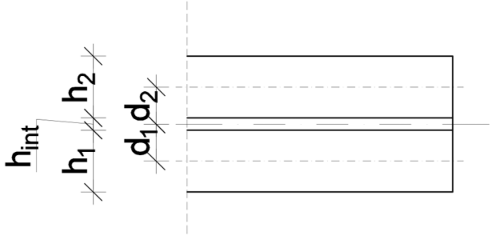
Analytical calculation – Effective thickness approach

CEN/TS 19100-2 (2021)

$$h_{eff,w} = \sqrt[3]{\frac{1}{\frac{\eta}{\sum_i h_i^3 + 12\sum_i (h_i \cdot d_i^2)} + \frac{1-\eta}{\sum_i h_i^3}}} \qquad (10)$$

$$h_{eff,\sigma,i} = \sqrt{\frac{1}{\frac{2 \cdot \eta \cdot |d_i|}{\sum_i h_i^3 + 12\sum_i (h_i \cdot d_i^2)} + \frac{h_i}{{h_{eff,w}}^3}}} \qquad (11)$$

$$\eta = \frac{1}{1 + \frac{h_{int} \cdot E \cdot n \cdot h^3 \cdot (n+1) \cdot \Psi_B}{12 G_{int} \cdot h^2 + (h + h_{int})^2 \cdot (n^2 - 1)}} \qquad (12)$$



h_i/h - the thickness of the glass plies

η - the coupling parameter depending on the shear stiffness of the interlayer, loading, and boundary conditions

Ψ_B - boundary coefficient

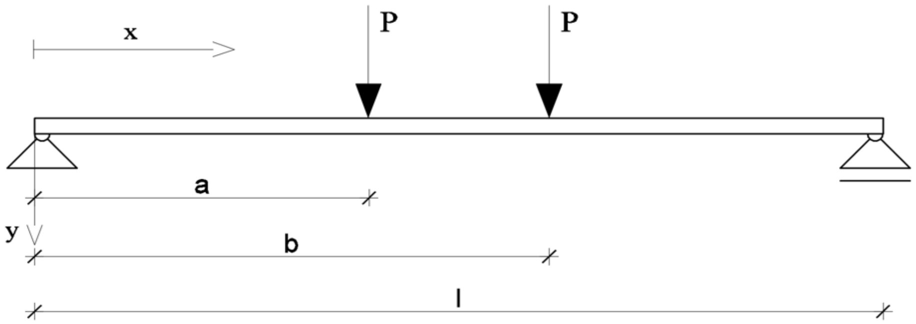
G_{int} – interlayer shear modulus

E – Youngs modulus for glass

n – number of plies

Analytical calculation – Effective thickness approach

CEN/TS 19100-2 (2021)



$$\sigma = \frac{M}{W_{ef,\sigma,j}} = \frac{M}{\frac{b * h_{ef,\sigma,j}{}^{2}}{6}}$$

$$w_{l/2} = \frac{1}{E \cdot I_{ef}} \cdot \left[\frac{P}{6} \cdot \left(-\left(\frac{l}{2}\right)^{3} + \left(\frac{l}{2} - a\right)^{3}\right)\right] + \left[\frac{P}{12} \cdot ((l)^3 - (l-a)^3 - (l-b)^3)\right]$$

Predictability assessment

Label	Number of glass plies	Thickness of glass plies	Type of glass	Type of interlayer	Thickness of interlayer	Test temperature	Experiments
VSG ESG 66.2 (EVA 0.76)	2	6 mm + 6 mm	Tempered	EVA	0.76	+23 ˚C	Pankhardt and Balázs (2010)
VSG ESG 66.2 (EVA 0.89)	2	6 mm + 6 mm	Tempered	EVA	0.89	+22 ˚C	Serafinavičius et al. (2013)
VSG ESG 1010.2 (EVA 0.76)	2	10 mm + 10 mm	Tempered	EVA	0.76	+20 to 23 ˚C	Hána et al. (2018)
VSG FG 44.4 (EVA 1.52)	2	4 mm + 4 mm	Float glass	EVA	1.52	Room t.	Castori and Speranzini (2017)

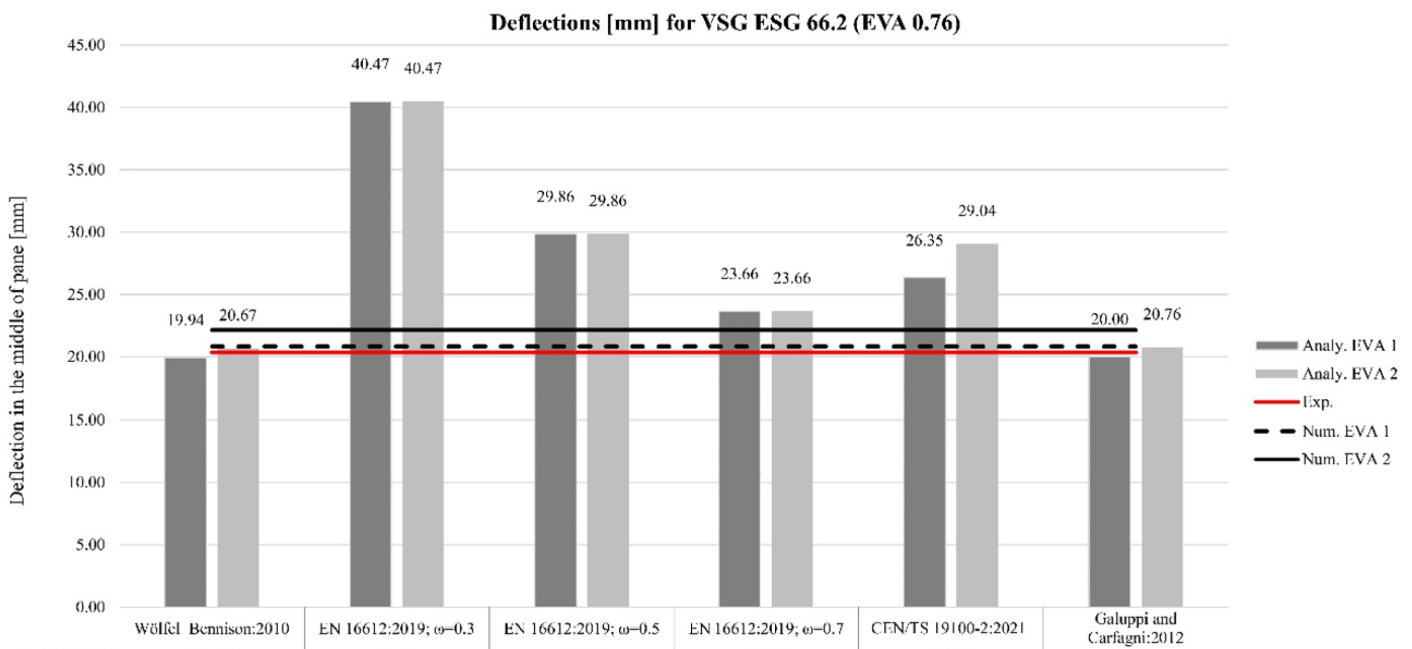
Comparison of Analytical, Numerical, and Experimental Predictions

Method / Value	Wölfel–Bennison	EN16612:2019 $\omega = 0.3$	EN16612:2019 $\omega = 0.5$	EN16612:2019 $\omega = 0.7$	Galuppi and Royer-Carfagni (2012)	CEN/TS 19100-2:2021
VSG ESG 66.2 (EVA 0.76)						
$h_{ef,w}$ [mm]	12.339	9.745	10.785	11.656	12.327	11.244
	12.192	9.745	10.785	11.656	12.175	10.886
$h_{ef,\sigma,j}$ [mm]	12.541	10.737	11.565	12.147	12.535	11.884
	12.461	10.737	11.565	12.147	12.452	11.638
VSG ESG 66.2 (EVA 0.89)						
$h_{ef,w}$ [mm]	12.395	9.812	10.876	11.765	12.381	11.139
	12.226	9.812	10.876	11.765	12.207	10.754
$h_{ef,\sigma,j}$ [mm]	12.631	10.822	11.671	12.266	12.624	11.857
	12.537	10.822	11.671	12.266	12.527	11.582
VSG ESG 1010.2 (EVA 0.76)						
$h_{ef,w}$ [mm]	19.708	15.984	17.623	19.003	19.678	17.569
	19.366	15.984	17.623	19.003	19.329	16.942
$h_{ef,\sigma,j}$ [mm]	20.200	17.571	18.865	19.875	20.184	18.826
	20.003	17.571	18.865	19.875	19.981	18.354
VSG FG 44.4 (EVA 1.52)						
$h_{ef,w}$ [mm]	9.070	7.030	7.903	8.617	9.058	7.708
	8.922	7.030	7.903	8.617	8.906	7.376
$h_{ef,\sigma,j}$ [mm]	9.279	7.837	8.545	9.021	9.272	8.40
	9.198	7.837	8.545	9.021	9.189	8.136

Comparison of Analytical, Numerical, and Experimental Predictions

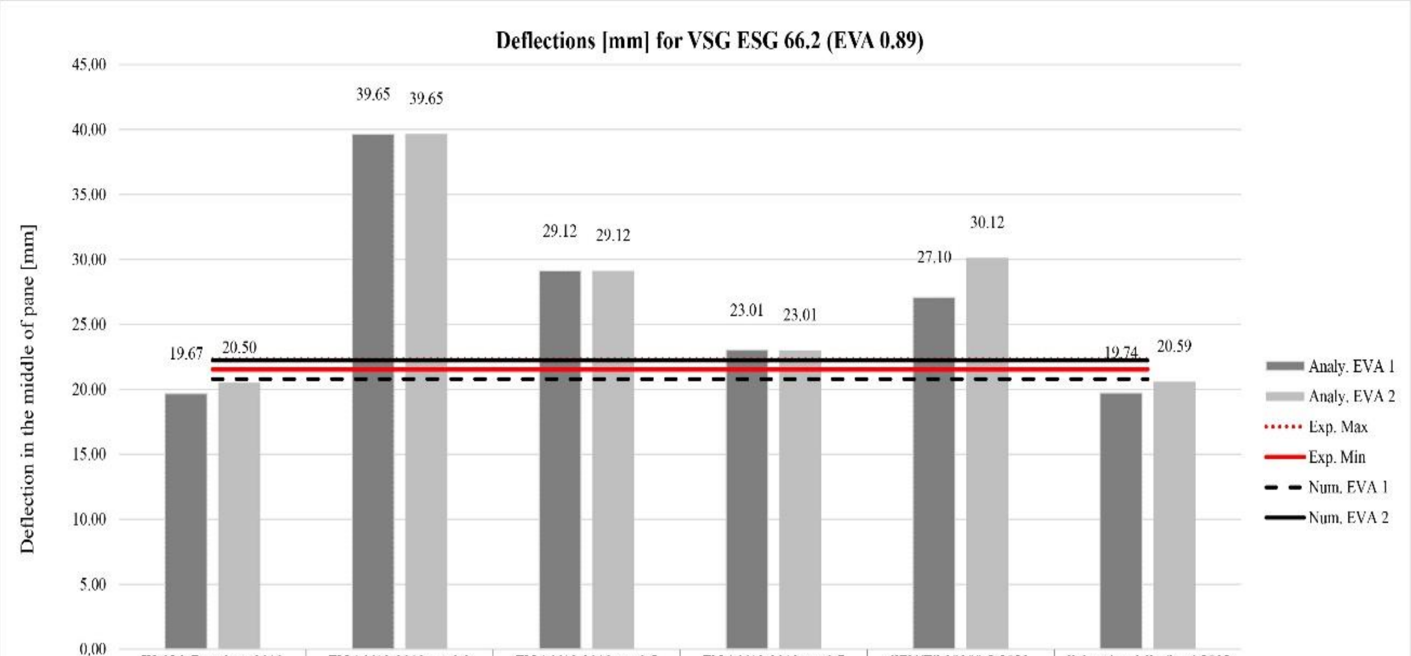
Method / Value	Wölfel–Bennison	EN16612:2019 ω=0.3	EN16612:2019 $\omega = 0.5$	EN16612:2019 $\omega = 0.7$	Galuppi and Royer-Carfagni (2012)	CEN/TS 19100-2:2021	Experiments	Num. results
VSG ESG 66.2 (EVA 0.76) **2P=4.0 kN**								
Defl. [mm]	19.94	40.47	29.86	23.66	20.00	26.35	20.35	20.829
	20.67	40.47	29.86	23.66	20.76	29.04		22.149
Stress [MPa]	84.77	115.65	99.69	90.36	84.86	94.41	/	94.21
	85.87	115.65	99.69	90.36	86.00	98.45		96.648
VSG ESG 66.2 (EVA 0.89) **2P=4.0 kN**								
Defl. [mm]	19.67	39.65	29.12	23.01	19.74	27.10	21.536 - 22.305	20.795
	20.50	39.65	29.12	23.01	20.59	30.12		22.22
Stress [MPa]	83.57	113.86	97.89	88.62	83.67	94.83	/	93.709
	84.83	113.86	97.89	88.62	84.97	99.40		96.331
VSG ESG 1010.2 (EVA 0.76) **2P=4.0 kN**								
Defl. [mm]	4.89	9.17	6.84	5.46	4.92	6.91	6.144	5.393
	5.16	9.17	6.84	5.46	5.19	7.70		5.8543
Stress [MPa]	32.68	43.19	37.47	34.06	32.73	37.62	35.181	37.188
	33.32	43.19	37.47	34.06	33.40	39.58		38.451
VSG FG 44.4 (EVA 1.52) **2P=0.6kN**								
Defl. [mm]	7.53	16.18	11.38	8.78	7.56	12.27	8.90 – 9.42	10.38
	7.91	16.18	11.38	8.78	7.95	14.00		10.842
Stress [MPa]	23.23	32.56	27.39	24.58	23.26	28.34	/	28.921
	23.64	32.56	27.39	24.58	23.69	30.21		29.523

Comparison of Analytical, Numerical, and Experimental Predictions



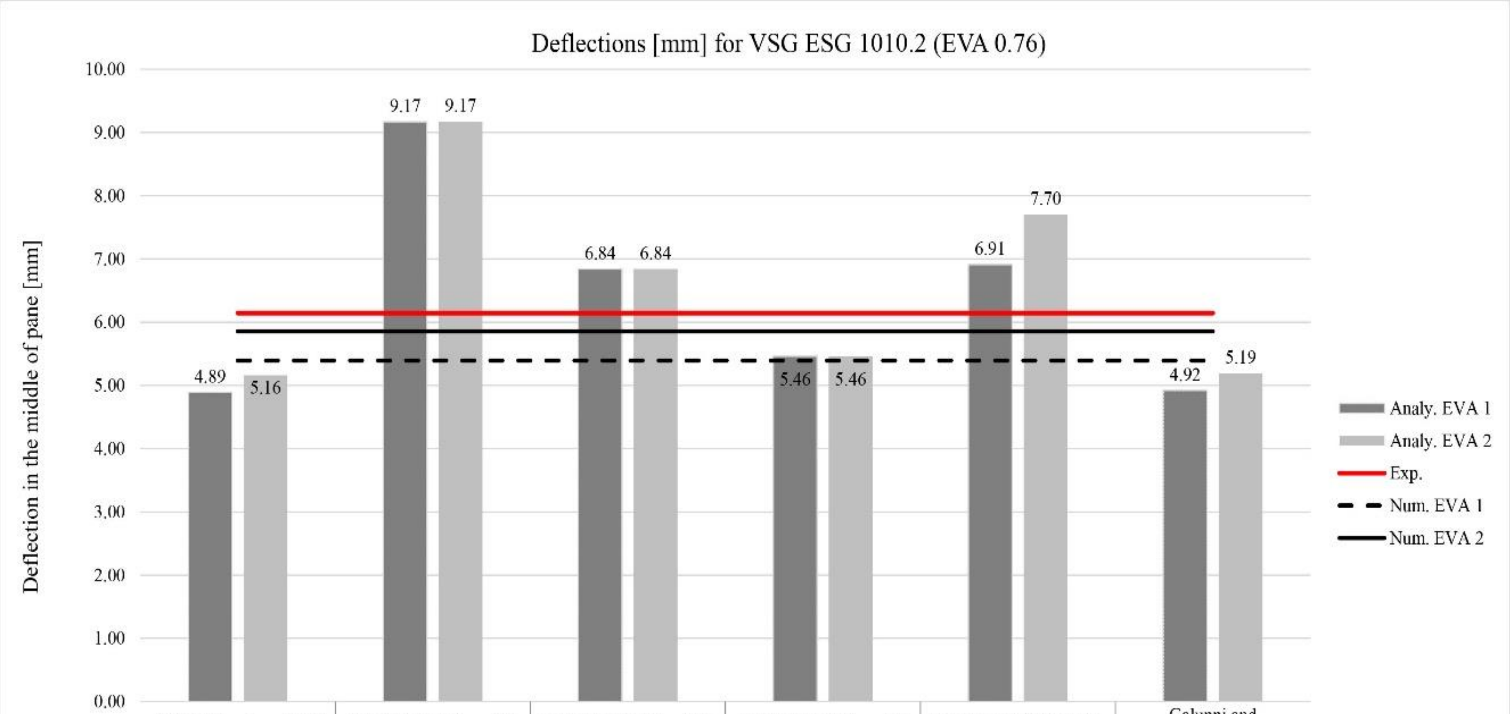
	Wölfel Bennison:2010	EN 16612:2019; ω=0.3	EN 16612:2019; ω=0.5	EN 16612:2019; ω=0.7	CEN/TS 19100-2:2021	Galuppi and Carfagni:2012
Analy. EVA 1	19.94	40.47	29.86	23.66	26.35	20.00
Analy. EVA 2	20.67	40.47	29.86	23.66	29.04	20.76
Exp.	20.35	20.35	20.35	20.35	20.35	20.35
Num. EVA 1	20.829	20.829	20.829	20.829	20.829	20.829
Num. EVA 2	22.149	22.149	22.149	22.149	22.149	22.149

Comparison of Analytical, Numerical, and Experimental Predictions



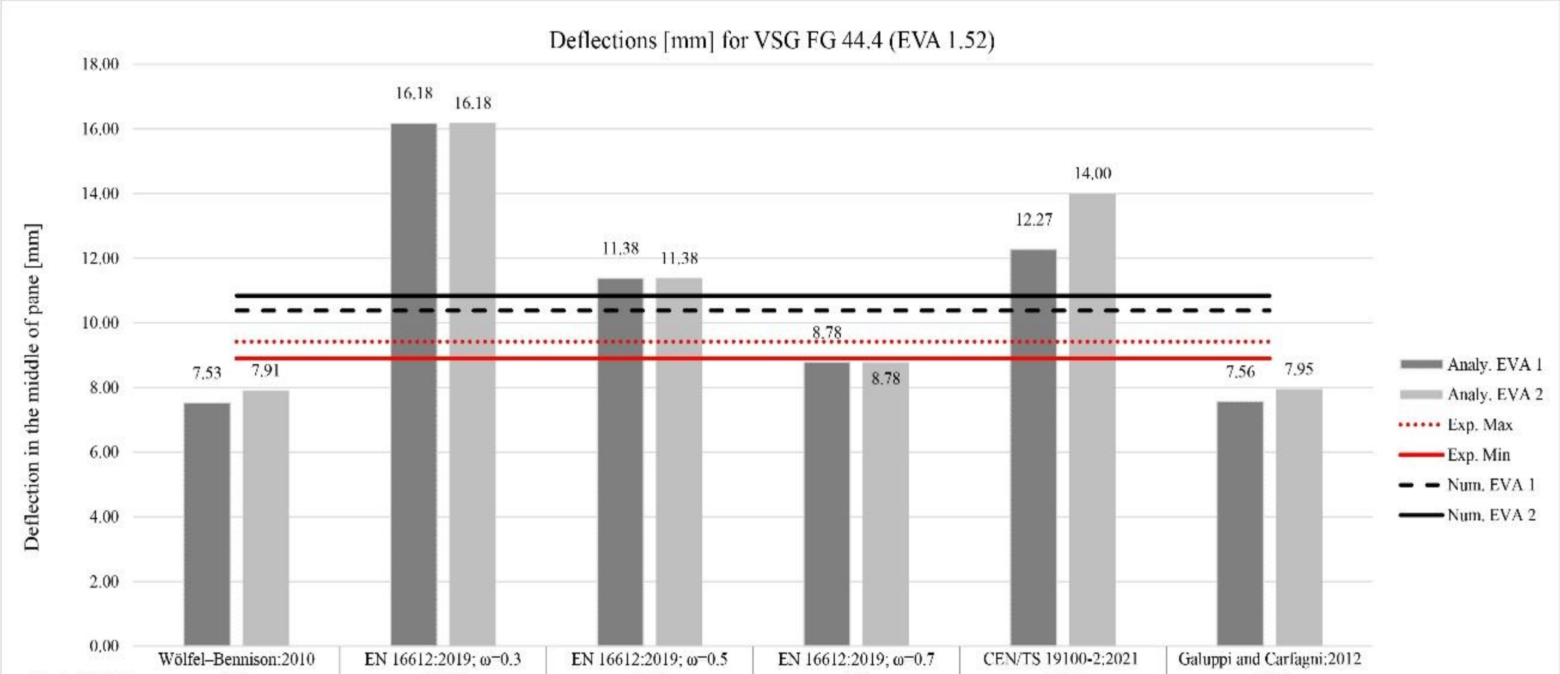
	Wölfel–Bennison:2010	EN 16612:2019; ω=0.3	EN 16612:2019; ω=0.5	EN 16612:2019; ω=0.7	CEN/TS 19100-2:2021	Galuppi and Carfagni;2012
Analy. EVA 1	19.67	39.65	29.12	23.01	27.10	19.74
Analy. EVA 2	20.50	39.65	29.12	23.01	30.12	20.59
Exp. Max	22.31	22.31	22.31	22.31	22.31	22.31
Exp. Min	21.54	21.54	21.54	21.54	21.54	21.54
Num. EVA 1	20.795	20.795	20.795	20.795	20.795	20.795
Num. EVA 2	22.22	22.22	22.22	22.22	22.22	22.22

Comparison of Analytical, Numerical, and Experimental Predictions



	Wölfel–Bennison:2010	EN 16612:2019; ω=0.3	EN 16612:2019; ω=0.5	EN 16612:2019; ω=0.7	CEN/TS 19100-2:2021	Galuppi and Carfagni:2012
Analy. EVA 1	4.89	9.17	6.84	5.46	6.91	4.92
Analy. EVA 2	5.16	9.17	6.84	5.46	7.70	5.19
Exp.	6.14	6.14	6.14	6.14	6.14	6.14
Num. EVA 1	5,393	5,393	5,393	5,393	5,393	5,393
Num. EVA 2	5,8543	5,8543	5,8543	5,8543	5,8543	5,8543

Comparison of Analytical, Numerical, and Experimental Predictions



	Wölfel–Bennison:2010	EN 16612:2019; ω=0.3	EN 16612:2019; ω=0.5	EN 16612:2019; ω=0.7	CEN/TS 19100-2;2021	Galuppi and Carfagni;2012
Analy. EVA 1	7.53	16.18	11.38	8.78	12.27	7.56
Analy. EVA 2	7.91	16.18	11.38	8.78	14.00	7.95
Exp. Max	9.42	9.42	9.42	9.42	9.42	9.42
Exp. Min	8.90	8.90	8.90	8.90	8.90	8.90
Num. EVA 1	10.38	10.38	10.38	10.38	10.38	10.38
Num. EVA 2	10.842	10.842	10.842	10.842	10.842	10.842

Summary and conclusion

The methods proposed by Galuppi and Royer-Carfagni (2012) and the Wölfel-Bennison approach showed the best agreement with experimental data.

The results obtained using the EN 16612-2019 standard for different values of the shear transfer coefficient ω did not show consistent accuracy.

The approach based on CEN/TS 19100-2 (2021) yielded stable and conservative predictions, especially for stress, making it a suitable option for practical design applications where safety is a priority.

In terms of predictive behaviour, it generally aligns with EN 16612-2019 for $\omega = 0.5$.

The FEM model developed in ANSYS effectively captured both stress and deformation behaviour, showing good agreement with experimental trends and validating the model assumptions and material characterization.

Thank you for Your attention!

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