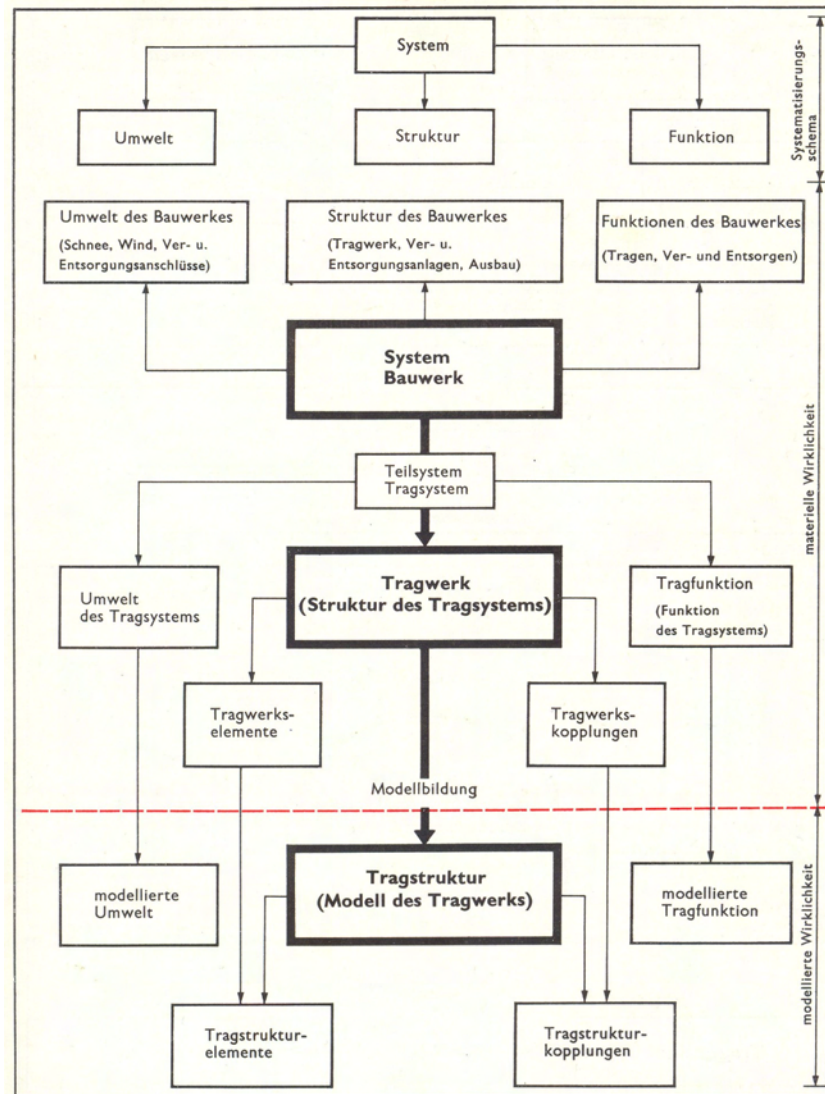


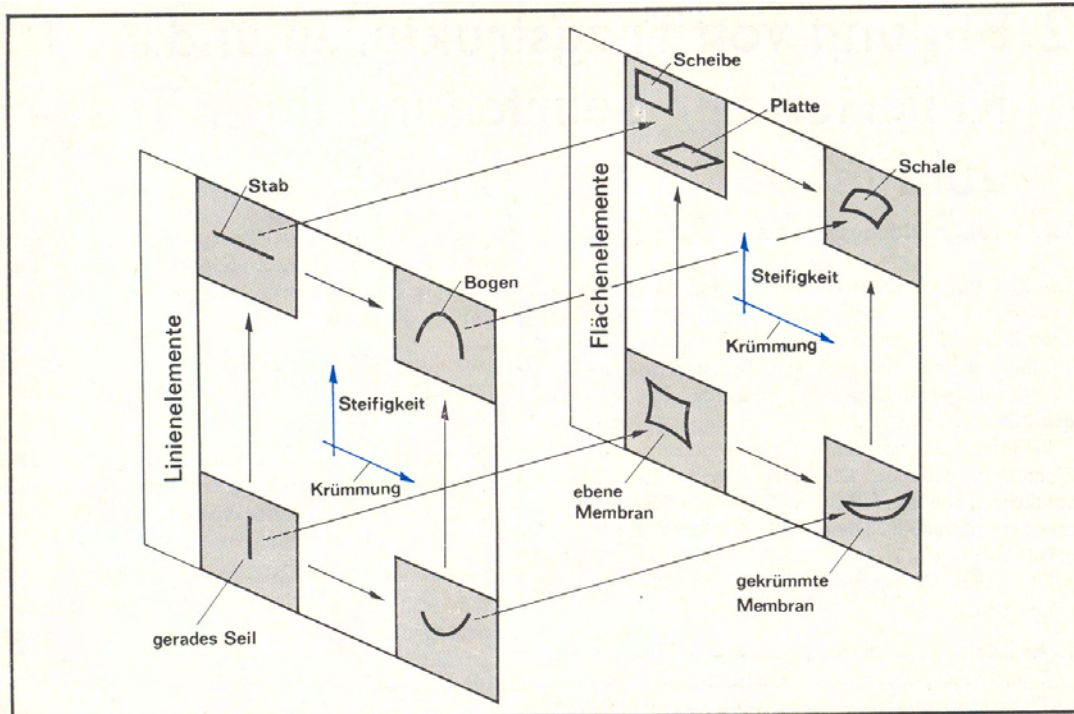
Puitkonstruktsioonide erikursus II

K. Õiger

Tallinn
2006-2007

VIII Ruumlikud katusekonstruktsioonid (võrkvõlv, ribikoorikvõlv, struktuurkandjad, tensegritid, kuplid, silinder-, konoid-, ja hüparkoorikud, ..., punkrid, silod), sh ruumlik püsivus

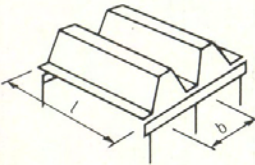
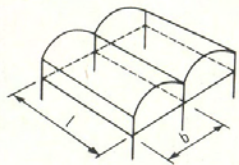
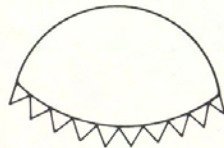
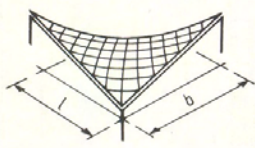
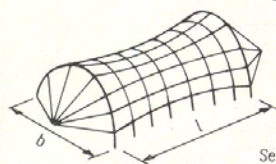
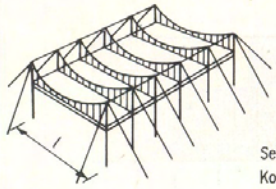


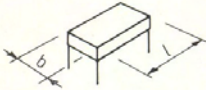
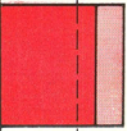
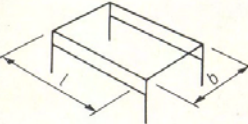
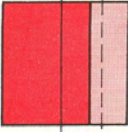
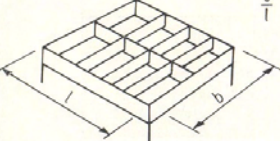

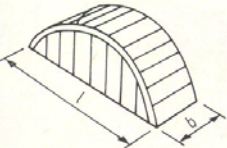

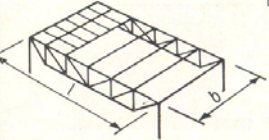

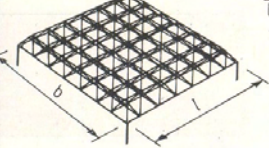



Tafel 1.2.3. Klassifizierung der Tragstrukturen

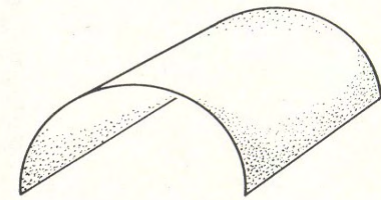
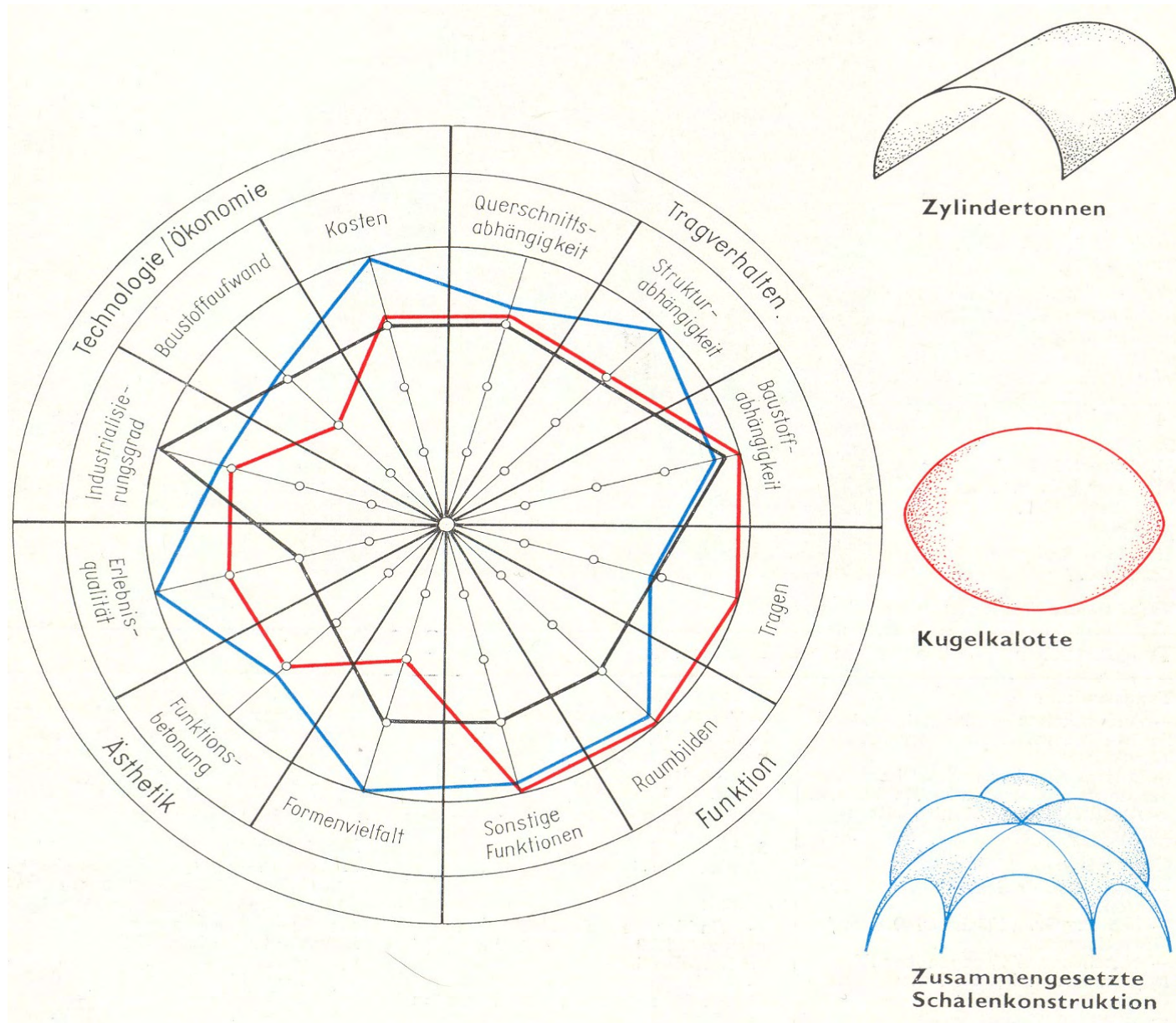
		Tragstrukturelemente							
		Linien-elemente				Flächen-elemente			
		Biegeweich		Biegesteif		Biegeweich		Biegesteif	
		gerade	gekrümmt	gerade	gekrümmt	gerade	gekrümmt	gerade	gekrümmt
Tragstrukturen	1-Dimensionale Tragstrukturen								
	2-Dimensionale Tragstrukturen								
	3-Dimensionale Tragstrukturen								
		gerade	gekrümmt	gerade	gekrümmt	eben	gekrümmt	eben	gekrümmt

		Flächenelemente				Linienelemente			
		biegesteif		biegeweich		biegesteif		biegeweich	
		Schale	Platte Scheibe	gekrümmte Membran	ebene Membran	Bogen	Stab	gekrümmtes Seil	gerades Seil
Linienelemente	biegeweich	gerades Seil							
		gekrümmtes Seil							
	biegesteif	Stab							
		Bogen							
Flächenelemente	biegeweich	ebene Membran					Tragstrukturen aus <i>gleichartigen</i> Strukturelementen zusammengesetzt.		
		gekrümmte Membran							
	biegesteif	Platte Scheibe			Tragstrukturen aus <i>verschiedenartigen</i> Strukturelementen zusammengesetzt.				
		Schale							

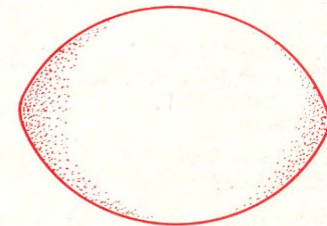
Bezeichnung	Tragstruktur	Spannweiten in (m)																		
		10	20	30	40	50	70	100	200	300	500									
relative biege-steife Flächen	 $\frac{b}{l} \approx \frac{1}{10}$ Faltwerke									█	█	█								
	 $\frac{b}{l} \approx \frac{1}{6}$ Zylindertonnen											█	█							
	 Kugelkalotten													█	█	█	█			
Kombination Biege-weiche Seile + Biege-steife Stäbe + Bogen	 $\frac{b}{l} \approx \frac{1}{1,5}$ Hyperbolische Paraboloid Seilnetz mit geraden Randträgern													█	█	█	█			
	 $\frac{b}{l} \approx \frac{1}{2}$ Seilnetz mit Randbogen															█	█	█	█	
	 Seibinder Kombination Seile + Stäbe																	█	█	█

Bezeichnung	Tragstruktur	Spannweiten in (m)									
		10	20	30	40	50	70	100	200	300	500
Biegesteife Stäbe + Bogen + Platten	 $\frac{b}{l} \approx \frac{1}{2}$ Platten										
	 $\frac{b}{l} \approx \frac{1}{3}$ Platte + Träger										
	 $\frac{b}{l} \approx \frac{2}{3}$ Haupt + Nebenträger										
	 $\frac{b}{l} \approx \frac{1}{5}$ Bogenbinder										
	 $\frac{b}{l} \approx \frac{1}{4}$ Fachwerkträger										
	 $\frac{b}{l} \approx 1,5$ Raumstabwerke										

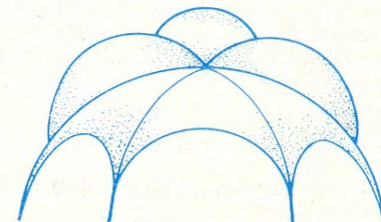
Katusekooorikud



Zylindertonnen

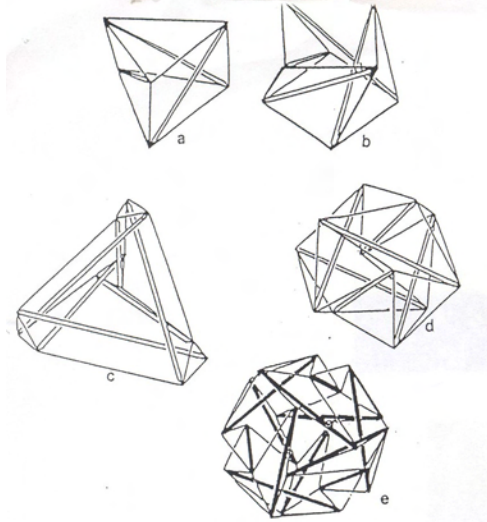


Kugelkalotte

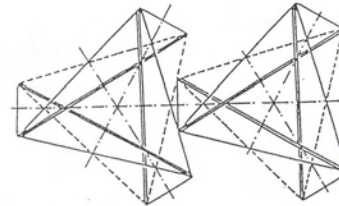


Zusammengesetzte Schalenkonstruktion

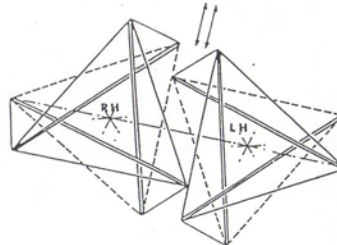
Tensegritid



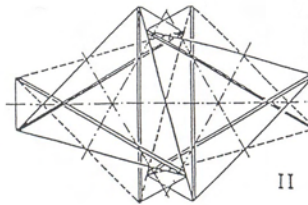
Tensegrity Polyhedra
 a) Triangular prism b) square prism
 c) Truncated Tetrahedron d) cuboctahedron



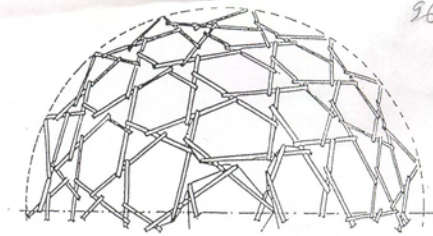
Ia.



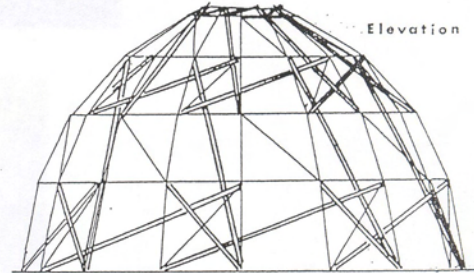
Ib



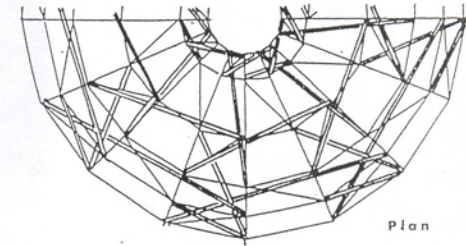
II



Fuller's Tensegrity Dome



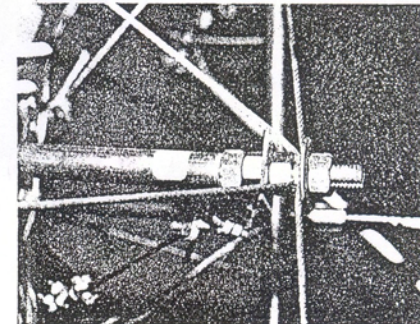
Elevation



Plan

Vilnay's Tensegrity Dome

Kuva 2. Tensegrity /2/.

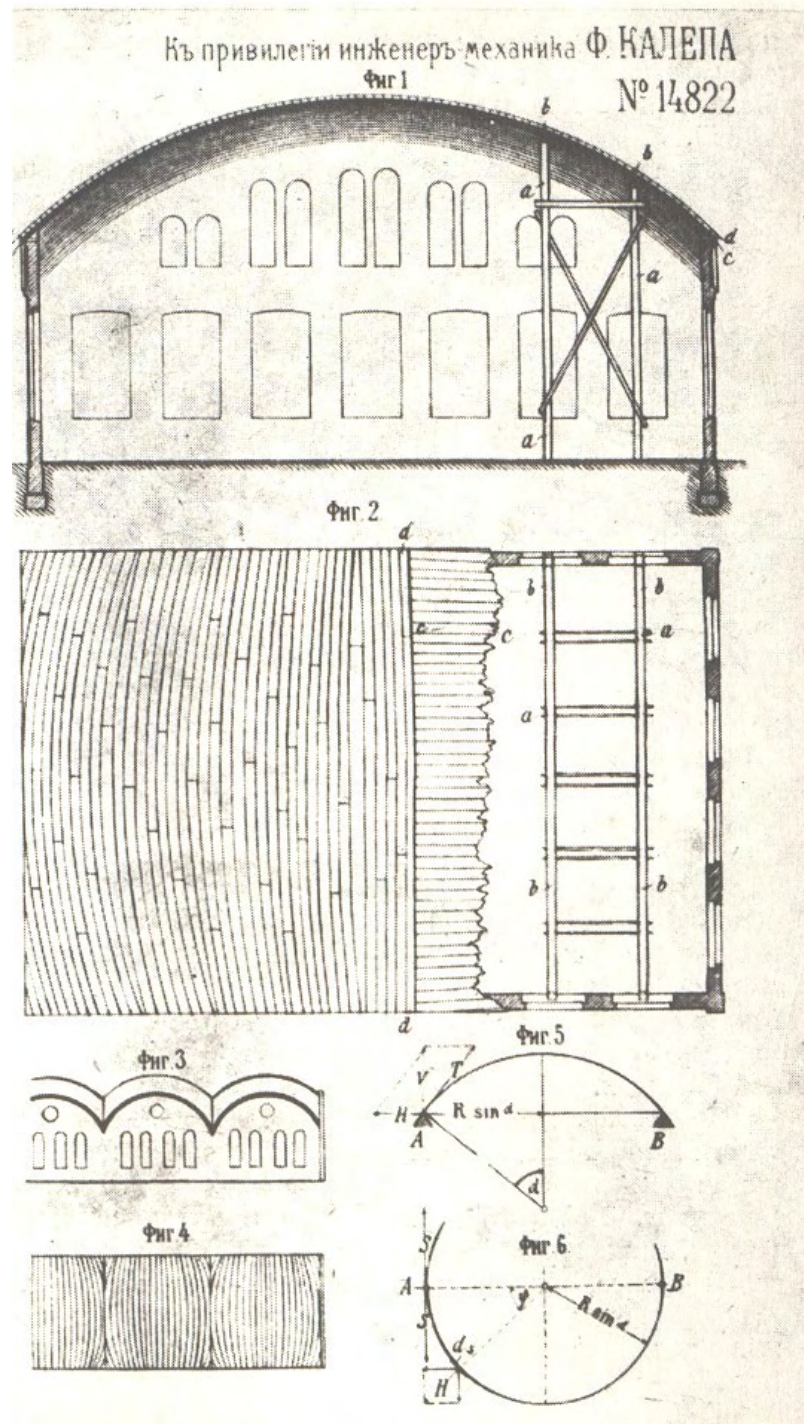


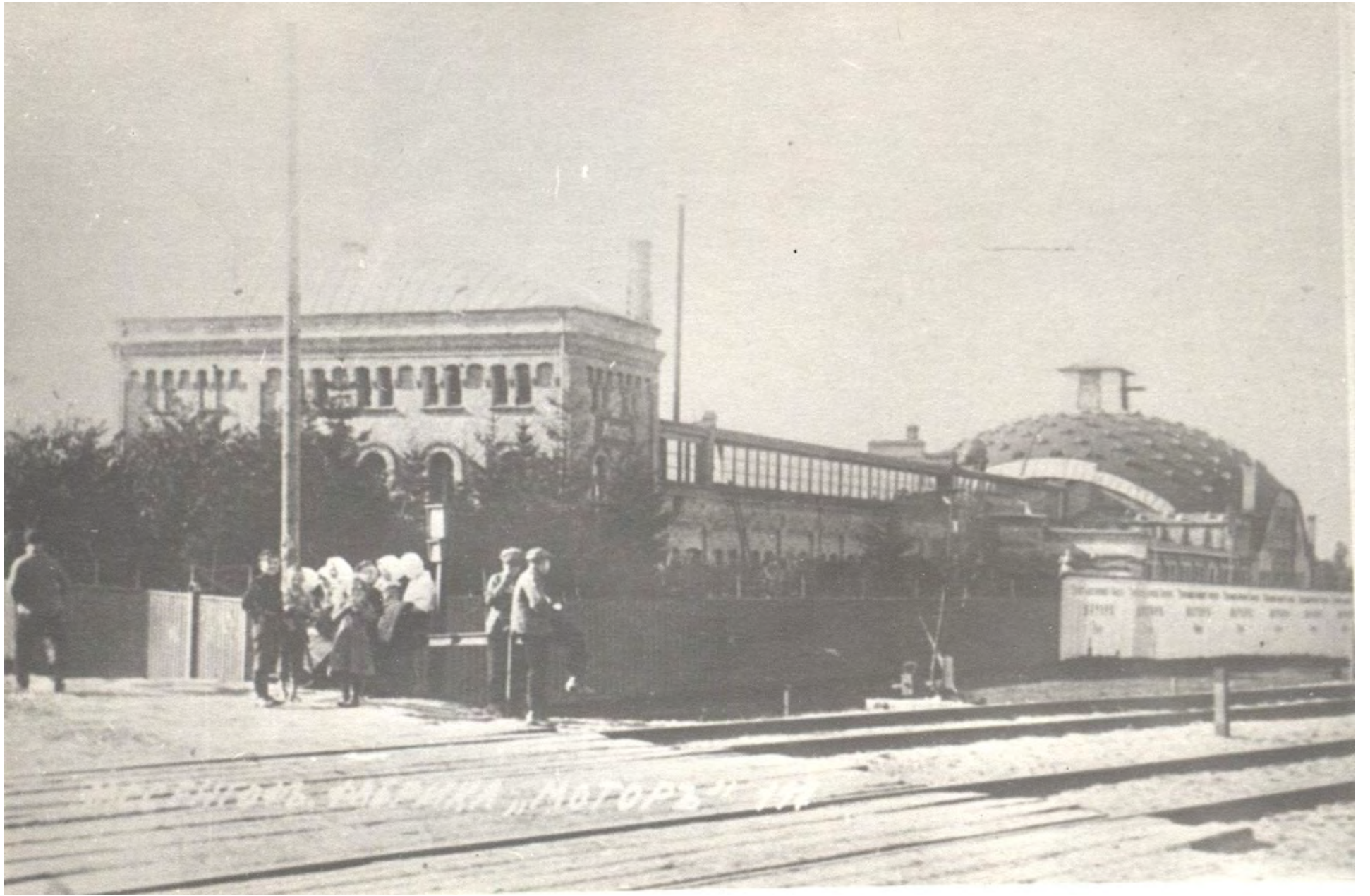
Ruumlike katusekonstruktsioonide arvutamisest

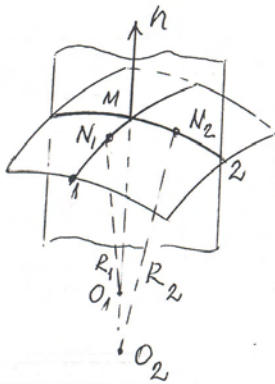
- ✓ Ruumlike katusekonstruktsioonide arvutamisel, nagu teistegi konstruktsioonide arvutamisel võib lähtuda
 - lineaarsest teooriast (füüsikaline ja geomeetriline lineaarsus – pingete ja deformatsioonide vahel kehtib lineaarne seos, väikesed paigutised, so koormuste ja sisejõudude, paigutiste vahel on lineaarne seos)
 - reeglina on tegemist aga õhukeste, suurte paigutistega konstruktsioonidega ja arvestada tuleb vähemalt geomeetrilise mittelineaarsusega

Vaatleme esialgu lineaarse teooria kohast analüüsi

Pisut ajalugu:
1905.a.



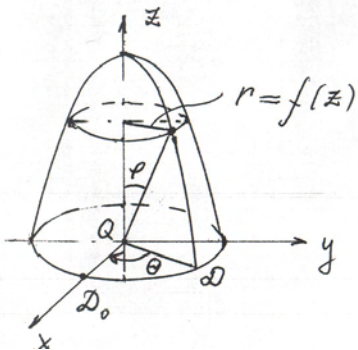
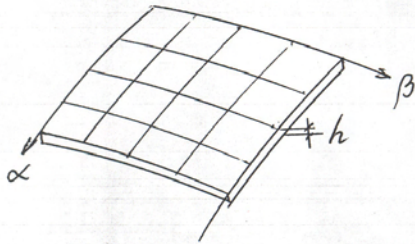




$$\frac{h}{R_{\min}} \leq \frac{1}{20} \div \frac{1}{10}$$

$$\frac{1}{1000} \leq \frac{h}{l} \leq \frac{1}{50}$$

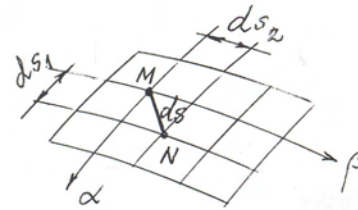
$$\frac{W}{h} < \frac{1}{5} \div \frac{1}{2}$$



$$1. \alpha = z, \beta = \theta$$

$$(z, \theta, r(z))$$

$$2. z = f(\varphi)$$

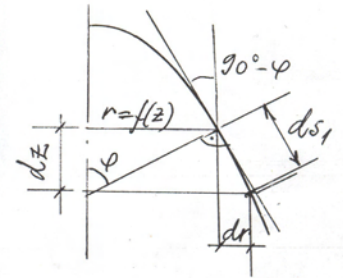
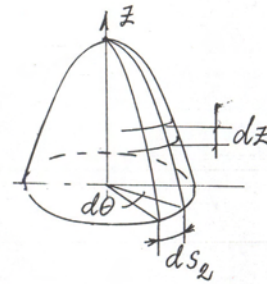


$$ds^2 = ds_1^2 + ds_2^2$$

$$ds_1 = A \cdot d\alpha, ds_2 = B \cdot d\beta$$

$$ds^2 = A^2 \cdot d\alpha^2 + B^2 \cdot d\beta^2$$

$$A = f(\alpha), B = f(\beta)$$



$$ds_2 = r \cdot d\theta$$

$$ds_1 = dz \frac{1}{\sin \varphi} = dz \sqrt{1 + \operatorname{ctg}^2 \varphi}$$

$$\operatorname{ctg} \varphi = \frac{dr}{dz}$$

$$dz \rightarrow 0$$

$$\frac{dr}{dz} = \operatorname{tg}(90^\circ - \varphi)$$

$$ds_1 = \sqrt{1 + \left(\frac{dr}{dz}\right)^2} dz$$

$$ds^2 = \left[1 + \left(\frac{dr}{dz}\right)^2\right] dz^2 + r^2 d\theta^2$$

$$A = \sqrt{1 + \left(\frac{dr}{dz}\right)^2} \quad B = r$$

3

$$A = \frac{r}{\cos \varphi} ; B = r$$

$$\alpha \rightarrow k_1 = \frac{1}{R_1} ; \beta \rightarrow k_2 = \frac{1}{R_2}$$

$$K = k_1 \cdot k_2 = \frac{1}{R_1} \cdot \frac{1}{R_2}$$



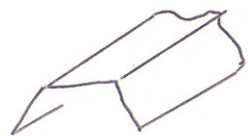
$$K = 0$$



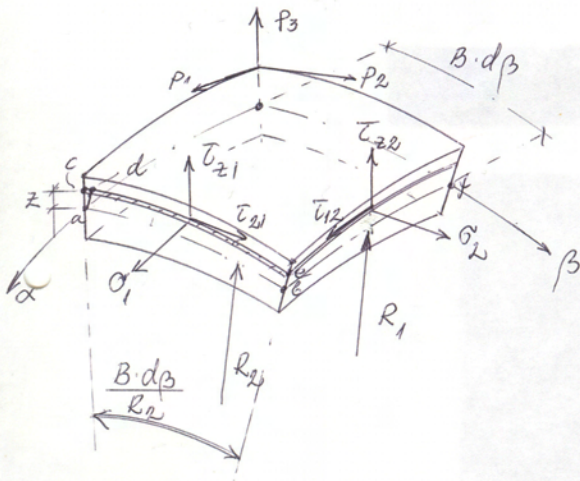
$$K = + \dots$$



$$K = - \dots$$



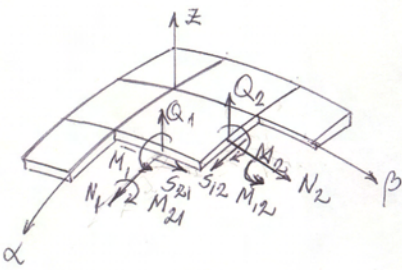
2.



$\alpha = \text{const}, \alpha + d\alpha = \text{const}$
 $\beta = \dots, \beta + d\beta = \dots$
 $\tau_{12} = \tau_{21}$

$$ce = ab + cd = B \cdot d\beta + \frac{B \cdot d\beta}{R_2} z = \left(1 + \frac{z}{R_2}\right) B \cdot d\beta$$

$$ef = \left(1 + \frac{z}{R_1}\right) A \cdot d\alpha$$



$$N_1 \cdot B d\beta = \int_{-\frac{h}{2}}^{\frac{h}{2}} \sigma_1 \left(1 + \frac{z}{R_2}\right) B \cdot d\beta \cdot dz$$

$$N_1 = \int_{-\frac{h}{2}}^{\frac{h}{2}} \sigma_1 \left(1 + \frac{z}{R_2}\right) dz$$

$$N_2 = \int_{-\frac{h}{2}}^{\frac{h}{2}} \sigma_2 \left(1 + \frac{z}{R_1}\right) dz$$

$$S_{12} = \int \tau_{12} \cdot \left(1 + \frac{z}{R_1}\right) dz$$

$$S_{21} = \int \tau_{21} \left(1 + \frac{z}{R_2}\right) dz$$

$$(B d\beta) M_1 = \int_{-\frac{h}{2}}^{\frac{h}{2}} \sigma_1 \left(1 + \frac{z}{R_2}\right) z \cdot dz (B d\beta)$$

$$M_2 = \int \sigma_2 \left(1 + \frac{z}{R_1}\right) z \cdot dz$$

$$M_{12} = \int \tau_{12} \left(1 + \frac{z}{R_1}\right) z \cdot dz$$

$$M_{21} = \int \tau_{21}$$

$$Q_1 = \int \tau_{21} \left(1 + \frac{z}{R_2}\right) dz$$

$$Q_2 = \int \tau_{22} \left(1 + \frac{z}{R_1}\right) dz$$

$$S_{12} \neq S_{21}; M_{12} \neq M_{21}$$

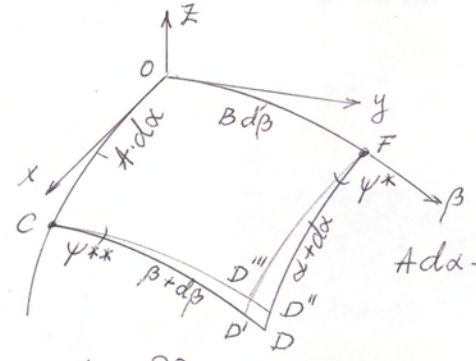
$$= = R_1 = R_2 \rightarrow$$

$$\frac{z}{R_1}; \frac{z}{R_2} \approx \frac{1}{\infty} \rightarrow S_{12} = S_{21}, M_{12} = M_{21}$$

$$\tau_{12} = \tau_{21}$$

$\sum_x F_i = ?; \sum_y F_i; \sum_z F_i = ?$

$\alpha = \text{const}$
 $\alpha + d\alpha = \text{const}$
 $\beta = \text{const}$
 $\beta + d\beta = \text{const}$



$$A d\alpha + \frac{\partial A}{\partial \beta} \cdot d\beta \cdot d\alpha$$

$$B d\beta + \frac{\partial B}{\partial \alpha} d\alpha \cdot d\beta$$

$$DD' = \frac{\partial B}{\partial \alpha} \cdot d\alpha \cdot d\beta \Rightarrow \Delta OF$$

$$DD'' = \frac{\partial A}{\partial \beta} \cdot d\beta \cdot d\alpha \Rightarrow \Delta OC$$

Normal force on OF:
 $N_1 \cdot B d\beta$

edge CD:

$$(N_1 + \frac{\partial N_1}{\partial \alpha} d\alpha)(B d\beta + \frac{\partial B}{\partial \alpha} d\alpha d\beta) =$$

$$= N_1 \cdot B d\beta + \frac{\partial N_1}{\partial \alpha} \cdot B \cdot d\alpha \cdot d\beta + N_1 \frac{\partial B}{\partial \alpha} \cdot d\alpha \cdot d\beta +$$

$$+ \frac{\partial N_1}{\partial \alpha} \cdot \frac{\partial B}{\partial \alpha} \cdot d\alpha^2 \cdot d\beta \rightarrow$$

$$N_1 \cdot B \cdot d\beta + \frac{\partial}{\partial \alpha} (N_1 \cdot B) d\alpha \cdot d\beta$$

or, for example edge OF:

$$S_{21} \cdot B \cdot d\beta$$

and CD:

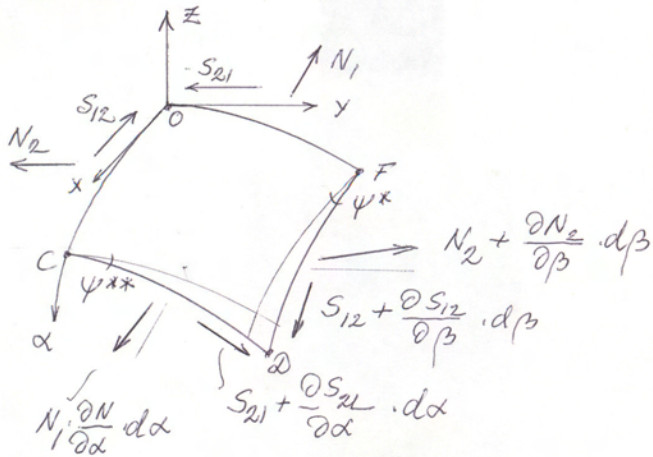
$$S_{21} \cdot B d\beta + \frac{\partial}{\partial \alpha} (S_{21} \cdot B) d\alpha \cdot d\beta$$

on M_1 , OF: $M_1 \cdot B d\beta$

$$CD: M_1 \cdot B d\beta + \frac{\partial}{\partial \alpha} (M_1 \cdot B) d\alpha \cdot d\beta \quad \text{and so on}$$

1. Equilibrium equations

$\sum X = 0:$



$$N_1: N_1 \cdot B d\beta + \frac{\partial}{\partial \alpha} (N_1 \cdot B) d\alpha \cdot d\beta - N_1 \cdot B d\beta = \frac{\partial}{\partial \alpha} (N_1 \cdot B) d\alpha \cdot d\beta$$

$$S_{12}: S_{12} \cdot A d\alpha + \frac{\partial}{\partial \beta} (S_{12} \cdot A) d\alpha \cdot d\beta - S_{12} \cdot A d\alpha = \frac{\partial}{\partial \beta} (S_{12} \cdot A) d\alpha \cdot d\beta$$

edge FD:

$$N_2: N_2 A d\alpha + \frac{\partial}{\partial \beta} (N_2 \cdot A) d\alpha \cdot d\beta$$

in plan ψ^*

$$\tan \psi^* = \frac{\partial'' \partial''}{F D''} \approx \frac{\partial' \partial'}{F D''}$$

$$\psi^* \approx \tan \psi^* \approx \frac{\frac{\partial B}{\partial \alpha} \cdot d\alpha \cdot d\beta}{A \cdot d\alpha}$$

$$-[N_2 A d\alpha + \frac{\partial}{\partial \beta} (N_2 \cdot A) d\alpha \cdot d\beta] \psi^* =$$

$$= -N_2 \frac{\partial B}{\partial \alpha} d\alpha \cdot d\beta - \frac{\partial}{\partial \beta} (N_2 \cdot A) \frac{\partial B}{\partial \alpha} \frac{1}{A} d\alpha d\beta^2 d\alpha^2 =$$

$$= -N_2 \frac{\partial B}{\partial \alpha} \cdot d\alpha \cdot d\beta$$

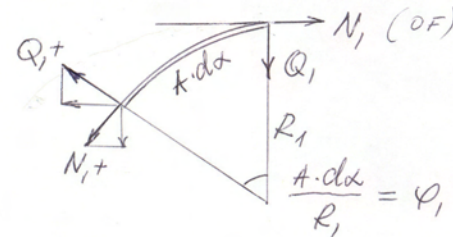
edge CD:

$$S_{21}: [S_{21} B d\beta + \frac{\partial}{\partial \alpha} (S_{21} \cdot B) d\alpha \cdot d\beta] \psi^{**}$$

$$\psi^{**} = \frac{\frac{\partial A}{\partial \beta} d\alpha \cdot d\beta}{B \cdot d\beta}$$

$$S_{21} = \frac{\partial A}{\partial \beta} d\alpha \cdot d\beta$$

Q_1 component:



$$\frac{1}{R_1} \cdot Q_1 \cdot A \cdot B \cdot d\alpha \cdot d\beta$$

$$\frac{A \cdot d\alpha}{R_1} = \psi_1$$

Load $p_1:$

$$p_1 \cdot A \cdot B \cdot d\alpha \cdot d\beta$$

$$1) \sum X = 0$$

$$\frac{\partial}{\partial \alpha} (N_1 \cdot B) + \frac{\partial}{\partial \beta} (S_{12} \cdot A) - N_2 \frac{\partial B}{\partial \alpha} + S_{21} \frac{\partial A}{\partial \beta} + Q_1 \frac{A \cdot B}{R_1} + AB \cdot p_1 = 0$$

$$2) \sum Y = 0$$

$$\frac{\partial}{\partial \beta} (N_2 \cdot A) + \frac{\partial}{\partial \alpha} (S_{21} \cdot B) - N_1 \frac{\partial A}{\partial \beta} + S_{12} \frac{\partial B}{\partial \alpha} + Q_2 \frac{A \cdot B}{R_2} + AB \cdot p_2 = 0$$

$$3) \sum Z = 0$$

$$Q_{1z}:$$

$$-Q_1 \cdot B \cdot d\beta + [Q_1 \cdot B d\beta + \frac{\partial}{\partial \alpha} (Q_1 \cdot B) dx \cdot d\beta]$$

$$\cos \varphi_1 \approx 1 \rightarrow$$

$$\frac{\partial}{\partial \alpha} (Q_1 \cdot B) dx \cdot d\beta$$

edge CD:

$$N_2$$

$$- [N_1 \cdot B d\beta + \frac{\partial}{\partial \alpha} (N_1 \cdot B) dx \cdot d\beta] \frac{A \cdot dx}{R_1}$$

$dx \cdot d\beta$

$$- N_1 \frac{AB}{R_1} dx \cdot d\beta$$

edges OC, DF:

$$\frac{\partial}{\partial \beta} (Q_2 \cdot A) dx \cdot d\beta ; - N_2 \frac{AB}{R_2} \cdot dx \cdot d\beta$$

Load

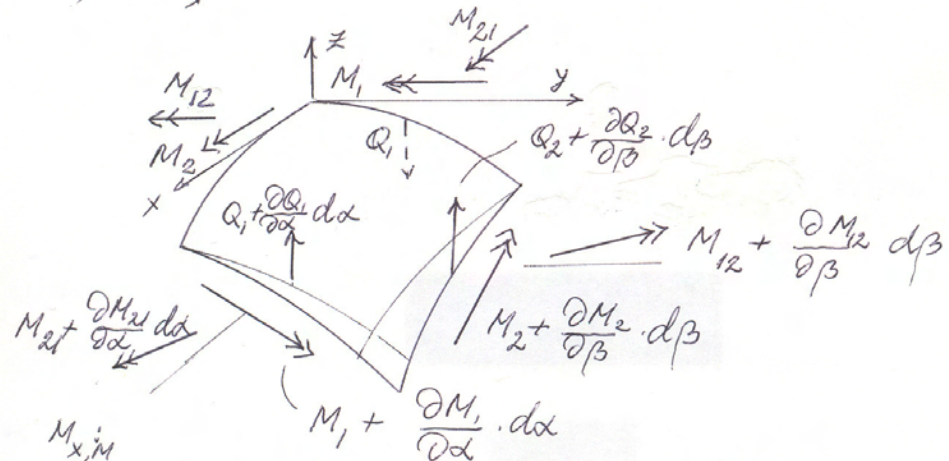
$$p_3 \cdot AB \cdot dx \cdot d\beta$$

$$\sum Z = 0$$

$$\frac{\partial}{\partial \alpha} (Q_1 \cdot B) + \frac{\partial}{\partial \beta} (Q_2 \cdot A) - N_1 \frac{AB}{R_1} - N_2 \frac{AB}{R_2} + AB \cdot p_3 = 0$$

$$S_{12} \approx S_{21} \approx 0$$

$$4) \sum M_y = 0$$



$M_{x,m}$

$$[- \frac{\partial}{\partial x} (M_{21} \cdot B) - \frac{\partial}{\partial \beta} (M_2 \cdot A) + M_1 \frac{\partial A}{\partial \beta} - M_{21} \frac{\partial B}{\partial \alpha}] dx \cdot d\beta$$

$M_{x,q}$

$$Q_2 \cdot A \cdot dx \cdot B d\beta$$

$$\sum M_x = 0$$

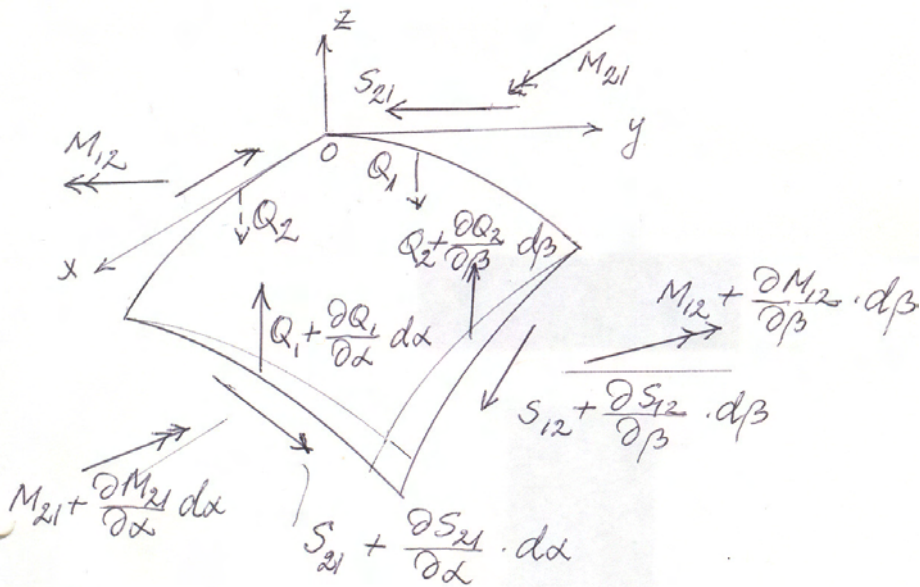
$$\frac{\partial (M_{21} \cdot B)}{\partial \alpha} + \frac{\partial (M_2 \cdot A)}{\partial \beta} - M_1 \frac{\partial A}{\partial \beta} + M_{12} \frac{\partial B}{\partial \alpha} - Q_2 \cdot AB = 0$$

$$M_{x,p} \approx 0$$

$$5) \sum M_y = 0$$

$$\frac{\partial (M_{12} \cdot A)}{\partial \beta} + \frac{\partial (M_1 \cdot B)}{\partial \alpha} - M_2 \frac{\partial B}{\partial \alpha} + M_{21} \frac{\partial A}{\partial \beta} - Q_1 \cdot AB = 0$$

$$6) \sum M_2 = 0$$



M_2, S_{21}, S_{12} :

$$S_{21} (B d\beta + \frac{\partial B}{\partial \alpha} d\beta d\alpha) A d\alpha -$$

$$- S_{12} (A d\alpha + \frac{\partial A}{\partial \alpha} d\alpha d\beta) B d\beta =$$

$$= (S_{21} - S_{12}) AB \cdot d\beta d\alpha$$

M_2, M_{21} :

$$M_{21} B d\beta \frac{A \cdot d\alpha}{R_1}$$

M_2, M_{12} :

$$- M_{12} A d\alpha \frac{B d\beta}{R_2}$$

$$M_{21} \approx 0$$



$$\sum M_2 = 0: AB d\alpha d\beta$$

$$S_{21} - S_{12} + \frac{M_{21}}{R_1} - \frac{M_{12}}{R_2} = 0$$

But

$$\int_{-\frac{h}{2}}^{\frac{h}{2}} \tau_{21} (1 + \frac{z}{R_2}) dz - \int \tau_{12} (1 + \frac{z}{R_2}) dz +$$

$$+ \frac{1}{R_1} \int \tau_{21} z (1 + \frac{z}{R_2}) dz - \frac{1}{R_2} \int \tau_{12} z (1 + \frac{z}{R_2}) dz =$$

$$= \int (\tau_{21} - \tau_{12}) (1 + \frac{z}{R_2}) (1 + \frac{z}{R_1}) dz$$

$$\tau_{21} = \tau_{12}$$

The equilibrium equations:

- 1) $\frac{\partial}{\partial \alpha} (BN_1) + N_2 \frac{\partial B}{\partial \alpha} + \frac{\partial}{\partial \beta} (A \cdot S_{12}) + S_{21} \frac{\partial A}{\partial \beta} + Q_1 k_1 AB$
 $+ AB p_1 = 0,$
- 2) $\frac{\partial}{\partial \beta} (AN_2) - N_1 \frac{\partial A}{\partial \beta} + \frac{\partial}{\partial \alpha} (BS_{21}) + S_{12} \frac{\partial B}{\partial \alpha} + Q_2 k_2 AB$
 $+ AB p_2 = 0,$
- 3) $-(k_1 N_1 + k_2 N_2) + \frac{1}{AB} [\frac{\partial}{\partial \alpha} (B \cdot Q_1) + \frac{\partial}{\partial \beta} (A Q_2)] + f.$

$$4) \frac{\partial}{\partial \alpha} (B \cdot M_{21}) + M_{12} \frac{\partial B}{\partial \alpha} + \frac{\partial}{\partial \beta} (A M_2) -$$

$$- M_1 \frac{\partial A}{\partial \beta} + Q_2 AB = 0,$$

$$5) \frac{\partial}{\partial \beta} (A \cdot M_{12}) + M_{21} \frac{\partial A}{\partial \beta} + \frac{\partial}{\partial \alpha} (B \cdot M_1) -$$

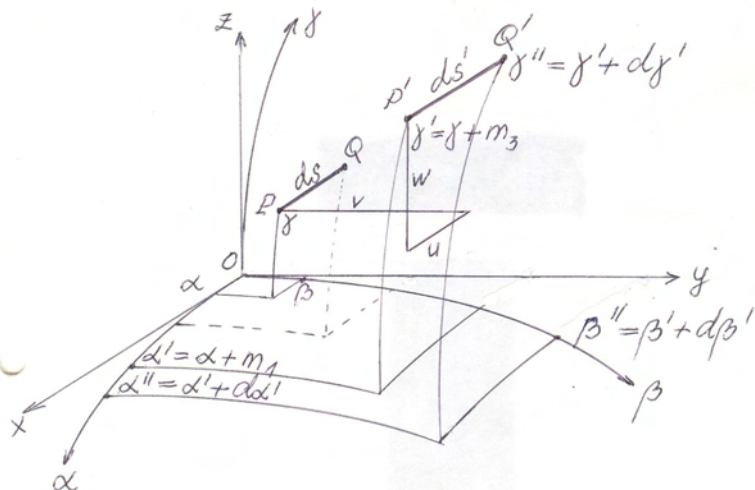
$$- M_2 \frac{\partial B}{\partial \alpha} - Q_1 AB = 0,$$

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$$N_1, N_2, S_{12}, S_{21}, M_1, M_2, M_{12}, M_{21}, Q_1, Q_2.$$

The geometrical equations

$$P(\alpha, \beta, \gamma), \\ Q(\alpha + d\alpha, \beta + d\beta, \gamma + d\gamma)$$



$ds \cos \theta = l, m, n$:

$$l = \cos(ds, x) = \frac{dx}{ds}$$

$$m = \cos(ds, y)$$

$$n = \cos(ds, z)$$

$$l \cdot ds = \tilde{A} d\alpha$$

$$m \cdot ds = \tilde{B} d\beta$$

$$n \cdot ds = \tilde{C} d\gamma$$

$$ds^2 = (\tilde{A} d\alpha)^2 + (\tilde{B} d\beta)^2 + (\tilde{C} d\gamma)^2$$

$PQ \rightarrow P'Q'$

$$P': \alpha' = \alpha + m_1$$

$$\beta' = \beta + m_2$$

$$\gamma' = \gamma + m_3$$

PP' projection

$$u = \tilde{A} \cdot m_1$$

$$v = \tilde{B} \cdot m_2$$

$$w = \tilde{C} \cdot m_3$$

$Q \rightarrow Q'(\alpha'', \beta'', \gamma'')$, $P'(\alpha', \beta', \gamma')$

Q' :

$$\alpha'' = \alpha' + d\alpha' = \alpha + m_1 + d\alpha + \frac{\partial m_1}{\partial \alpha} d\alpha + \frac{\partial m_1}{\partial \beta} d\beta + \frac{\partial m_1}{\partial \gamma} d\gamma$$

$$\beta'' = \beta' + d\beta' = \beta + m_2 + d\beta + \frac{\partial m_2}{\partial \alpha} d\alpha + \frac{\partial m_2}{\partial \beta} d\beta + \frac{\partial m_2}{\partial \gamma} d\gamma$$

$$\gamma'' = \gamma' + d\gamma' = \gamma + m_3 + d\gamma + \frac{\partial m_3}{\partial \alpha} d\alpha + \dots$$

Taylor serie

$$\tilde{A}_1 = \tilde{A} + \frac{\partial \tilde{A}}{\partial \alpha} \cdot m_1 + \frac{\partial \tilde{A}}{\partial \beta} \cdot m_2 + \frac{\partial \tilde{A}}{\partial \gamma} \cdot m_3$$

$$\tilde{B}_1 = \tilde{B} + \frac{\partial \tilde{B}}{\partial \alpha} \cdot m_1 + \dots$$

$$\tilde{C}_1 = \tilde{C} + \frac{\partial \tilde{C}}{\partial \alpha} \cdot m_1 + \dots$$

ds' projections:

$$l' \cdot ds' = \tilde{A}_1 (\alpha'' - \alpha')$$

$$m' \cdot ds' = \tilde{B}_1 (\beta'' - \beta')$$

$$n' \cdot ds' = \tilde{C}_1 (\gamma'' - \gamma')$$

$$\tilde{A}_1, \alpha'', \alpha' \rightarrow$$

$$l' \cdot ds' = \tilde{A}_1 (\alpha'' - \alpha') = \left(\tilde{A} + \frac{\partial \tilde{A}}{\partial \alpha} \cdot m_1 + \frac{\partial \tilde{A}}{\partial \beta} \cdot m_2 + \frac{\partial \tilde{A}}{\partial \gamma} \cdot m_3 \right) (d\alpha + \frac{\partial m_1}{\partial \alpha} d\alpha + \frac{\partial m_1}{\partial \beta} d\beta + \frac{\partial m_1}{\partial \gamma} d\gamma)$$

high degree

$$l' \cdot ds' = \tilde{A} d\alpha + \frac{\partial \tilde{A}}{\partial \alpha} \cdot m_1 \cdot d\alpha + \frac{\partial \tilde{A}}{\partial \alpha} \cdot m_2 \cdot d\alpha + \frac{\partial \tilde{A}}{\partial \alpha} \cdot m_3 \cdot d\alpha + \tilde{A} \frac{\partial m_1}{\partial \alpha} d\alpha + \tilde{A} \frac{\partial m_1}{\partial \beta} d\beta + \tilde{A} \frac{\partial m_1}{\partial \gamma} d\gamma$$

$$- + - = \frac{\partial}{\partial \alpha} (\tilde{A} \cdot m_i)$$

$$\rightarrow A \cdot d\alpha = l \cdot ds, \rightarrow m_i = \frac{u}{\tilde{A}}, m_2 = \frac{v}{\tilde{B}}, m_3 = \frac{w}{\tilde{C}}$$

$$l' ds' = l ds \left(1 + \frac{1}{\tilde{A}} \frac{\partial u}{\partial \alpha} + \frac{v}{\tilde{A}\tilde{B}} \frac{\partial \tilde{A}}{\partial \beta} + \frac{w}{\tilde{A}\tilde{C}} \frac{\partial \tilde{A}}{\partial \gamma} \right) +$$

$$+ m ds \frac{\tilde{A}}{\tilde{B}} \frac{\partial}{\partial \beta} \left(\frac{u}{\tilde{A}} \right) + n ds \frac{\tilde{A}}{\tilde{C}} \frac{\partial}{\partial \gamma} \left(\frac{u}{\tilde{A}} \right),$$

$$m' ds' = \dots$$

$$n' ds' = \dots$$

$$(P'Q')^2 = (l' ds')^2 + (m' ds')^2 + (n' ds')^2$$

$$PQ \rightarrow \varepsilon$$

$$\varepsilon = \frac{P'Q' - PQ}{PQ}$$

$$P'Q' = PQ(1 + \varepsilon) = ds(1 + \varepsilon)$$

$$(1 + \varepsilon)^2 ds^2 = ds^2 \left[l \left(1 + \frac{1}{\tilde{A}} \frac{\partial u}{\partial \alpha} + \frac{v}{\tilde{A}\tilde{B}} \frac{\partial \tilde{A}}{\partial \beta} + \frac{w}{\tilde{A}\tilde{C}} \frac{\partial \tilde{A}}{\partial \gamma} \right) + m \frac{\tilde{A}}{\tilde{B}} \frac{\partial}{\partial \beta} \left(\frac{u}{\tilde{A}} \right) + n \frac{\tilde{A}}{\tilde{C}} \frac{\partial}{\partial \gamma} \left(\frac{u}{\tilde{A}} \right) \right]^2 +$$

$$+ \left[l \frac{\tilde{B}}{\tilde{A}} \frac{\partial}{\partial \alpha} \left(\frac{v}{\tilde{B}} \right) + m(1 + \dots) \right]^2$$

$$u^2, v^2, w^2 \approx 0, \frac{\partial u}{\partial \alpha} \dots \approx 0, l^2 + m^2 + n^2 = 1 \Rightarrow$$

$$\varepsilon = \varepsilon_1 \cdot l^2 + \varepsilon_2 \cdot m^2 + \varepsilon_3 \cdot n^2 + \gamma_{12} \cdot l +$$

$$+ \gamma_{23} \cdot m \cdot n + \gamma_{31} \cdot n \cdot l,$$

where

$$\varepsilon_1 = \frac{1}{\tilde{A}} \frac{\partial u}{\partial \alpha} + \frac{v}{\tilde{A}\tilde{B}} \frac{\partial \tilde{A}}{\partial \beta} + \frac{w}{\tilde{A}\tilde{C}} \frac{\partial \tilde{A}}{\partial \gamma};$$

$$\varepsilon_2 = \frac{1}{\tilde{B}} \frac{\partial v}{\partial \beta} + \frac{u}{\tilde{A}\tilde{B}} \frac{\partial \tilde{B}}{\partial \alpha} + \frac{w}{\tilde{A}\tilde{C}} \frac{\partial \tilde{B}}{\partial \gamma};$$

$$\varepsilon_3 = \frac{1}{\tilde{C}} \frac{\partial w}{\partial \gamma} + \frac{v}{\tilde{B}\tilde{C}} \frac{\partial \tilde{C}}{\partial \beta} + \frac{u}{\tilde{A}\tilde{C}} \frac{\partial \tilde{C}}{\partial \alpha};$$

$$\gamma_{12} = \frac{\tilde{B}}{\tilde{A}} \frac{\partial}{\partial \alpha} \left(\frac{v}{\tilde{B}} \right) + \frac{\tilde{A}}{\tilde{B}} \frac{\partial}{\partial \beta} \left(\frac{u}{\tilde{A}} \right),$$

$$\gamma_{23} = \frac{\tilde{C}}{\tilde{B}} \frac{\partial}{\partial \beta} \left(\frac{w}{\tilde{C}} \right) + \frac{\tilde{B}}{\tilde{C}} \frac{\partial}{\partial \gamma} \left(\frac{v}{\tilde{B}} \right),$$

$$\gamma_{31} = \frac{\tilde{A}}{\tilde{C}} \frac{\partial}{\partial \gamma} \left(\frac{u}{\tilde{A}} \right) + \frac{\tilde{C}}{\tilde{A}} \frac{\partial}{\partial \alpha} \left(\frac{w}{\tilde{C}} \right)$$

$$\varepsilon_1 \rightarrow x, \varepsilon_2 \rightarrow y, \varepsilon_3 \rightarrow z$$

$$\gamma_{12} \rightarrow xy, \gamma_{23} \rightarrow yz, \gamma_{31} \rightarrow xz$$

When thin shell: $\alpha, \beta, z \Rightarrow$

$$\varepsilon_3 = \gamma_{13} = \gamma_{23} = 0$$

$$\tilde{A} = A \left(1 + \frac{z}{R_1} \right) \quad (I)$$

$$\tilde{B} = B \left(1 + \frac{z}{R_2} \right)$$

$$\tilde{C} = 1 \rightarrow \gamma - z \text{ lin.}$$

$$\tilde{A}, \tilde{B}, \tilde{C} \rightarrow \varepsilon_3=0, \gamma_{13}=0, \gamma_{23}=0;$$

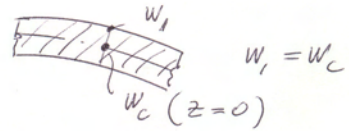
$$(1) \quad \frac{\partial w}{\partial z} = 0; \quad (II)$$

$$(2) \quad \frac{1}{B \left(1 + \frac{z}{R_2} \right)} \frac{\partial w}{\partial \beta} + B \left(1 + \frac{z}{R_2} \right) \frac{\partial}{\partial z} \left[\frac{v}{B \left(1 + \frac{z}{R_2} \right)} \right] = 0$$

$$(3) \quad A \left(1 + \frac{z}{R_1} \right) \frac{\partial}{\partial z} \left[\frac{u}{A \left(1 + \frac{z}{R_1} \right)} \right] + \frac{1}{A \left(1 + \frac{z}{R_1} \right)} \frac{\partial w}{\partial \alpha} =$$

$\int \mathbf{I} d\mathbf{z}$:

$$W = W(\alpha, \beta)$$



$$(2) \rightarrow \left(\frac{\partial v}{\partial z} \right)_{z=0} = \frac{v_0}{R_2} - \frac{1}{B} \cdot \frac{\partial W}{\partial \beta}$$

$$(3) \rightarrow \left(\frac{\partial u}{\partial z} \right)_{z=0} = \frac{u_0}{R_1} - \frac{1}{B} \cdot \frac{\partial W}{\partial \alpha}$$

$$\int : \quad \begin{aligned} v &= v_0 + z \left(\frac{v_0}{R_2} - \frac{1}{B} \cdot \frac{\partial W}{\partial \beta} \right) \\ u &= u_0 + z \left(\frac{u_0}{R_1} - \frac{1}{A} \frac{\partial W}{\partial \alpha} \right) \end{aligned} \quad (\text{III})$$

$$(I), (II), (III) \text{ and } \frac{\partial \tilde{A}}{\partial z} = \frac{A}{R_1}; \quad \frac{\partial \tilde{B}}{\partial z} = \frac{B}{R_2} \Rightarrow$$

$$\rightarrow \epsilon_1, \epsilon_2, \epsilon_3, \gamma_{12} :$$

$$\epsilon_1 = \left(\frac{1}{A} \cdot \frac{\partial u}{\partial \alpha} + \frac{v}{AB} \cdot \frac{\partial A}{\partial \beta} + \frac{W}{R_1} \right) - z \left[\frac{1}{A} \cdot \frac{\partial}{\partial \alpha} \left(-\frac{u}{R_1} + \frac{1}{A} \cdot \frac{\partial W}{\partial \alpha} \right) + \frac{1}{AB} \left(-\frac{v}{R_2} + \frac{1}{B} \cdot \frac{\partial W}{\partial \beta} \right) \frac{\partial A}{\partial \beta} \right],$$

$$\epsilon_2 = \left(\frac{1}{B} \cdot \frac{\partial v}{\partial \beta} + \frac{u}{AB} \frac{\partial B}{\partial \alpha} + \frac{W}{R_2} \right) - z \left[\frac{1}{B} \frac{\partial}{\partial \beta} \left(-\frac{v}{R_2} + \frac{1}{B} \cdot \frac{\partial W}{\partial \beta} \right) + \frac{1}{A} \left(-\frac{u}{R_1} + \frac{1}{A} \frac{\partial W}{\partial \alpha} \right) \frac{\partial B}{\partial \alpha} \right],$$

$$\gamma_{12} = \left[\frac{B}{A} \cdot \frac{\partial}{\partial \alpha} \left(\frac{v}{B} \right) + \frac{A}{B} \frac{\partial}{\partial \beta} \left(\frac{u}{A} \right) \right] + z \left[\frac{B}{A} \frac{\partial}{\partial \alpha} \cdot \frac{1}{B} \left(\frac{v_0}{R_2} - \frac{1}{B} \frac{\partial W}{\partial \beta} \right) + \frac{A}{B} \frac{\partial}{\partial \beta} \cdot \frac{1}{A} \left(\frac{u_0}{R_1} - \frac{1}{A} \frac{\partial W}{\partial \alpha} \right) \right].$$

or

$$\epsilon_1 = \epsilon_{10} + z \epsilon_1', \quad \epsilon_2 = \epsilon_{20} + z \cdot \epsilon_2'$$

$$\gamma_{12} = \gamma_0 + 2z \cdot \chi$$

where

$$\epsilon_{10} = \frac{1}{A} \cdot \frac{\partial u_0}{\partial \alpha} + \frac{v_0}{AB} \cdot \frac{\partial A}{\partial \beta} + \frac{W_0}{R_1},$$

$$\epsilon_{20} = \frac{1}{B} \frac{\partial v_0}{\partial \beta} + \frac{u_0}{AB} \cdot \frac{\partial B}{\partial \alpha} + \frac{W_0}{R_2},$$

$$\gamma_0 = \frac{B}{A} \frac{\partial}{\partial \alpha} \left(\frac{v_0}{B} \right) + \frac{A}{B} \frac{\partial}{\partial \beta} \left(\frac{u_0}{A} \right),$$

$$\epsilon_1' = -\frac{1}{A} \cdot \frac{\partial}{\partial \alpha} \left(-\frac{u_0}{R_1} + \frac{1}{A} \cdot \frac{\partial W_0}{\partial \alpha} \right) - \frac{1}{AB} \left(-\frac{v_0}{R_2} + \frac{1}{B} \cdot \frac{\partial W_0}{\partial \beta} \right) \frac{\partial A}{\partial \beta},$$

$$\epsilon_2' = -\frac{1}{B} \cdot \frac{\partial}{\partial \beta} \left(-\frac{v_0}{R_2} + \frac{1}{B} \cdot \frac{\partial W_0}{\partial \beta} \right) - \frac{1}{AB} \left(-\frac{u_0}{R_1} + \frac{1}{A} \cdot \frac{\partial W_0}{\partial \alpha} \right) \frac{\partial B}{\partial \alpha},$$

$$\chi = \frac{1}{2} \left[\frac{B}{A} \cdot \frac{\partial}{\partial \alpha} \cdot \frac{1}{B} \left(\frac{v_0}{R_2} - \frac{1}{B} \cdot \frac{\partial W}{\partial \beta} \right) + \frac{A}{B} \cdot \frac{\partial}{\partial \beta} \cdot \frac{1}{A} \left(\frac{u_0}{R_1} - \frac{1}{A} \cdot \frac{\partial W}{\partial \alpha} \right) \right]$$

$\epsilon_{10}, \epsilon_{20}, \gamma_0$ - central surface def.

Physical equations.

$$\sigma_1 = \frac{E}{1-\nu^2} (\epsilon_1 + \nu \epsilon_2)$$

$$\sigma_2 = \frac{E}{1-\nu^2} (\epsilon_2 + \nu \epsilon_1)$$

$$\tau_{12} = G \gamma_{12}$$

$\epsilon_{11}, \epsilon_{22}, \gamma_{12} \Rightarrow \sigma_i, (\sigma_{22}, \tau_{12}) \Rightarrow N_1, N_2$ and so on:

$$N_1 = \frac{E}{1-\nu^2} \int_{-\frac{h}{2}}^{\frac{h}{2}} \left(1 + \frac{z}{R_2}\right) [\epsilon_{10} + \nu \epsilon_{20} + z(\alpha_1 + \nu \alpha_2)] dz$$

$$N_2 = \frac{E}{1-\nu^2} \int \left(1 + \frac{z}{R_1}\right) [\epsilon_{20} + \nu \epsilon_{10} + z(\alpha_2 + \nu \alpha_1)] dz$$

$$S_{12} = G \int (\gamma_0 + 2z\chi) \left(1 + \frac{z}{R_2}\right) dz$$

$$S_{21} = G \int (\gamma_0 + 2z\chi) \left(1 + \frac{z}{R_1}\right) dz$$

$$M_1 = \frac{E}{1-\nu^2} \int z \left(1 + \frac{z}{R_2}\right) [\epsilon_{10} + \nu \epsilon_{20} + z(\alpha_1 + \nu \alpha_2)] dz$$

$$M_2 = \frac{E}{1-\nu^2} \int z \left(1 + \frac{z}{R_1}\right) [\epsilon_{20} + \nu \epsilon_{10} + z(\alpha_2 + \nu \alpha_1)] dz$$

$$M_{12} = G \int z \left(1 + \frac{z}{R_1}\right) (\gamma_0 + 2z\chi) dz$$

$$M_{21} = G \int z \left(1 + \frac{z}{R_2}\right) (\gamma_0 + 2z\chi) dz$$

$$\gamma_{13} = \gamma_{23} = 0 \Rightarrow \tau_{13} = \tau_{23} = 0 \Rightarrow Q_1 = Q_2 = 0$$

But Q_1 and Q_2 from equilibrium equations? contradiction? - specious

$$\left(1 + \frac{z}{R_1}\right) \approx \left(1 + \frac{z}{R_2}\right) \approx 1:$$

$$N_1 = \frac{Eh}{1-\nu^2} (\epsilon_{10} + \nu \epsilon_{20})$$

$$N_2 = \frac{Eh}{1-\nu^2} (\epsilon_{20} + \nu \epsilon_{10})$$

$$S = S_{12} = S_{21} = Gh\gamma_0$$

$$M_1 = D(\alpha_1 + \nu \alpha_2)$$

$$M_2 = D(\alpha_2 + \nu \alpha_1)$$

$$M_{12} = M_{21} = D(1-\nu)\chi$$

Boundary conditions

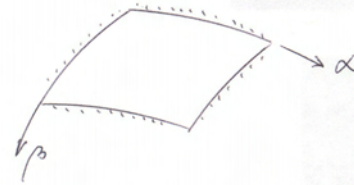
5 - egl. equations

6 - geom. eq.

6 - physical -

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data on shells, where



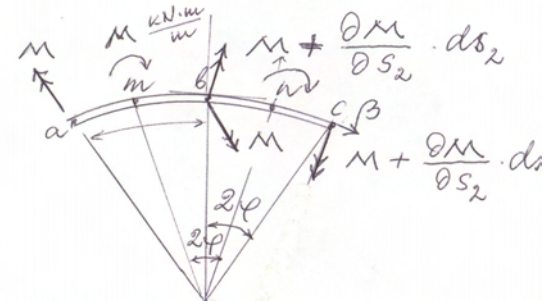
kinematic cond.

$$u = v = w = 0, \quad \psi = 0$$

Statical cond.

$$N_1 = Q_1 = S = M_1 = \dot{M}$$

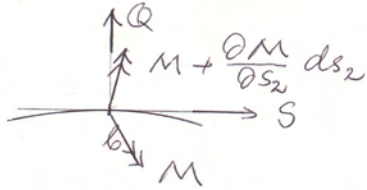
let it be $\alpha = \text{const}$



$$ab = bc = ds_2$$

$$m \rightarrow \frac{\dot{M}}{ds_2}$$

$$w \rightarrow \frac{\partial M}{\partial s_2} ds_2$$



Projection forces in b :

$$\uparrow \frac{\partial M}{\partial s_2} ds_2 + M - M = \frac{\partial M}{\partial s_2} ds_2$$

$$\rightarrow (2M + \frac{\partial M}{\partial s_2} ds_2) \varphi$$

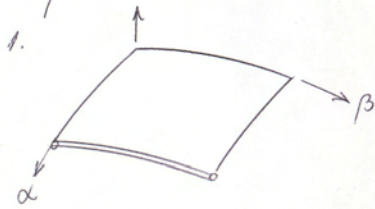
$$ds_2 \rightarrow 2\varphi = \frac{ds_2}{R_2}$$

$$\frac{M}{R_2} ds_2 \rightarrow +S$$

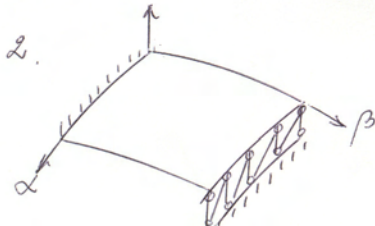
and now

$$\left. \begin{aligned} N_1 &= 0 \\ M_1 &= 0 \\ \bar{Q}_1 &= Q_1 + \frac{1}{B} \frac{\partial M}{\partial \beta} = 0 \\ \bar{S} &= S + \frac{M}{R_2} = 0 \end{aligned} \right\} 4$$

Often mixed cond.

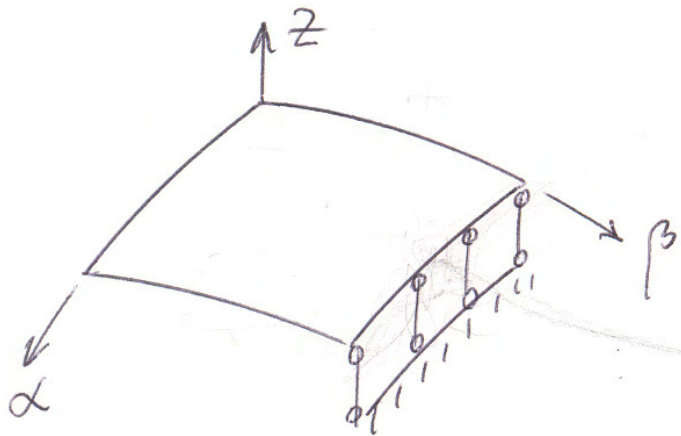


$$\begin{aligned} \alpha &= \text{const} \\ w &= 0; u = 0 \\ M_1 &= 0, V = 0 \end{aligned}$$



$$\begin{aligned} \beta &= \text{const} \\ w &= 0; M_2 = 0 \\ u &= 0; N_2 = 0 \end{aligned}$$

3. Hinge



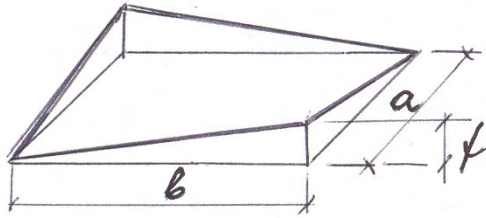
$$\beta = \text{const}$$

$$w = 0; \quad M_2 = 0$$

$$N_2 = 0$$

$$S = 0$$

Shallow shells



$$f \leq \frac{1}{5} a$$

$$z = f_1(x) + f_2(y)$$

$$k_1 = \frac{\partial^2 z}{\partial x^2} = f_1''(x); \quad k_2 = f_2''(y)$$

Fundamentals:

a) shallow $\alpha = x, \beta = y$

$$ds^2 = dx^2 + dy^2$$

$$A = B = 1$$

(1)

in initial equations $K = k_1 \cdot k_2 \approx 0$

b) static hypothesis

$$k_i \cdot M, \quad \frac{\partial k_i}{\partial t} \cdot M$$

eq. equations

$$\frac{\partial N_1}{\partial x} + \frac{\partial S}{\partial y} + p_1 = 0 \quad (I)$$

$$\frac{\partial N_2}{\partial y} + \frac{\partial S}{\partial x} + p_2 = 0 \quad (II)$$

$$-k_1 \cdot N_1 - k_2 \cdot N_2 + \frac{\partial Q_1}{\partial x} + \frac{\partial Q_2}{\partial y} + p_3 = 0 \quad (III) \quad (2)$$

$$\frac{\partial M}{\partial x} + \frac{\partial M_2}{\partial y} - Q_2 = 0 \quad (IV)$$

$$\frac{\partial M}{\partial y} + \frac{\partial M_1}{\partial x} - Q_1 = 0 \quad (V)$$

geom. eq. (central surface)

$$\varepsilon_1 = \frac{\partial u}{\partial x} + k_1 \cdot w$$

$$\varepsilon_2 = \frac{\partial v}{\partial y} + k_2 \cdot w \quad (3)$$

$$\gamma = \frac{\partial v}{\partial y} + \frac{\partial u}{\partial x}$$

$$\alpha_1 = -\frac{\partial^2 w}{\partial x^2}; \quad \alpha_2 = -\frac{\partial^2 w}{\partial y^2} \quad (4)$$

$$\chi = -\frac{\partial^2 w}{\partial x \partial y}$$

phys. relations

$$N_1 = \frac{Eh}{1-\nu^2} (\varepsilon_1 + \nu \varepsilon_2)$$

$$N_2 = \dots$$

$$S = Gh\gamma$$

$$M_1 = D(\alpha_1 + \nu \alpha_2)$$

$$M_2 = \dots$$

$$M = M_{12} = M_{21} = D(1-\nu)\chi$$

(5)

Possibilities to solve the problem:

$$\frac{Q_1}{(IV)}, \frac{Q_2}{(V)} \rightarrow (III),$$

$$(3) \rightarrow (5) \rightarrow (2) \quad \} \text{ 3 equations}$$

1) System of 3 eq. can be varied to 2 connected between equations when an 2 unknown w, φ .

and membrane forces are expressed in foll. form

$$N_1 = \frac{\partial^2 \varphi}{\partial y^2}; \quad N_2 = \frac{\partial^2 \varphi}{\partial x^2}; \quad S = -\frac{\partial^2 \varphi}{\partial x \partial y} \quad (6)$$

where:

$$p_1 = p_2 = 0$$

then (6) \rightarrow (III):

$$-k_1 \frac{\partial^2 \varphi}{\partial y^2} - k_2 \frac{\partial^2 \varphi}{\partial x^2} - 2 \frac{\partial^2}{\partial x^2} \nabla^2 W -$$
$$- 2 \frac{\partial^2}{\partial y^2} \nabla^2 W + p_3 = 0$$

or

$$\nabla_k^2 \varphi + 2 \nabla^2 \nabla^2 W - p_3 = 0,$$

where $\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$

$$\nabla_k^2 = k_1 \frac{\partial^2}{\partial y^2} + k_2 \frac{\partial^2}{\partial x^2}$$

To get the second eq. (we use the compatibility condition):

$$(3) \rightarrow u, v \quad \frac{\partial}{\partial y} \frac{\partial}{\partial y} \varepsilon_1, \quad \frac{\partial}{\partial x} \frac{\partial}{\partial x} \varepsilon_2:$$

$$k_1 = \frac{\partial^2 \varepsilon_1}{\partial y^2}; \quad k_2 = \frac{\partial^2 \varepsilon_2}{\partial x^2} \quad \text{and} \quad \frac{\partial^2 \gamma}{\partial x \partial y} \quad (7)$$

$$\frac{\partial^2 \varepsilon_1}{\partial y^2} + \frac{\partial^2 \varepsilon_2}{\partial x^2} = \frac{\partial^2 \gamma}{\partial x \partial y} + k_1 \frac{\partial^2 w}{\partial y^2} + k_2 \frac{\partial^2 w}{\partial x^2} \quad (9)$$

(5), (6) $\rightarrow \varepsilon_1, \varepsilon_2, \gamma \Rightarrow$ (9):

$$\frac{1}{Eh} \nabla^2 \nabla^2 \varphi - \nabla_k^2 W = 0 \quad \text{compatibility cond.}$$

$$\begin{cases} \nabla_k^2 \varphi + 2 \nabla^2 \nabla^2 W - p_3 = 0 & \text{--- III equl. eq.} \\ \frac{1}{Eh} \nabla^2 \nabla^2 \varphi - \nabla_k^2 W = 0 & \text{--- compatib.} \end{cases} \quad (10)$$

If $p_1 = p_2 = 0$ $k_1 = \text{const}$ $k_2 = -\nu$ for shallow translation surface

if shallow arbitrary surface: $z = f(x, y)$
 $k_1 = f_1(x, y); k_2 = f_2(x, y) :$

$$(10) \Rightarrow \nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} ,$$
$$\nabla_k^2 = \frac{\partial}{\partial x} (k_2 \frac{\partial}{\partial x}) + \frac{\partial}{\partial y} (k_1 \frac{\partial}{\partial y})$$

If we know φ, w that satisfy boundary conditions then we can find from

$$(6) \rightarrow N_1, N_2, S = - \frac{\partial^2 \varphi}{\partial x \partial y}$$
$$(4) \rightarrow x_1, x_2, \chi = - \frac{\partial^2 w}{\partial x \partial y}$$
$$(5) \rightarrow M_1, M_2, M = D(1-\nu)\chi$$

$$(2) \frac{IV}{V} \rightarrow Q_2$$
$$(2) \frac{IV}{V} \rightarrow Q_1$$

(10) includes two problems
a) plane stress state
b) plate bending

i.e. If $k_1 = 0, k_2 = 0$
 $\nabla_k^2 = 0 ;$

$$\nabla^2 \nabla^2 w = \frac{P_3}{D} \quad \text{Sophie Sermeu-Lagrange}$$

$$\nabla^2 \nabla^2 \varphi = 0 \quad \text{Maxwell - Bri biharmon.}$$

i.e two separate equations

How to solve the equations?

If $k_1 = \text{const}$
 $k_2 = \text{const}$
shallow shell

to solve directly
- difficult task
(error).

There is rational ^{and effective} to use the variational methods.

1) Bubnov-Galerkin's method

exa. solution is substitute with approximately one so that boundary cond. are satisfied.

For example:

$$F(x, \psi, \psi', \dots, \psi^n) = 0 \quad (11)$$

$$\psi = \sum_1^n a_n \psi_n \quad (12) \text{ appr. solution}$$

ψ_n - satisfies bound. cond.

a_n - const. coeff. to be determined

Now there are used the quality of orthonormal functions

$$\int \psi_i(x) \psi_k(x) dx = 0 \quad i \neq k$$

or
$$\int_a^b \psi_i(\psi_n) \psi_k(\psi_n) dx = 0, \quad i \neq k$$

(12) \rightarrow (11):

$$F(x, a_1, \psi_1, \dots, a_n, \psi_n, a'_1, \psi_1', \dots) \neq 0$$

to determine a_i

$$\int_{\Omega} F(x, a_i, \psi_1, \dots, a_n, \psi_n) \psi_i dx = 0$$

- algebraic diff. eq.

Usually


$$\varphi = \sum_m \sum_n A_{mn} \cdot \varphi_{mn}$$

$$W = \sum_m \sum_n B_{mn} \cdot W_{mn}$$

$$p_3 = \sum_m \sum_n C_{mn} \cdot Z_{mn}$$

2) Finite difference method:

For example for hyper:



$$\frac{\partial u^2}{\partial x^2} + \frac{(1-\nu)}{2} \frac{\partial^2 v}{\partial y^2} + \frac{(1+\nu)}{2} \frac{\partial^2 v}{\partial x \partial y} - (1-\nu) S_0 \frac{\partial w}{\partial y} + \frac{p_x}{k} = 0$$

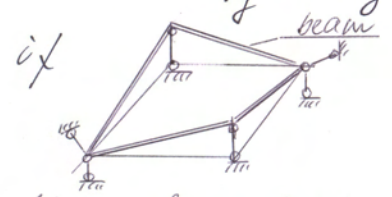
$$\frac{\partial v^2}{\partial y^2} + \frac{(1-\nu)}{2} \frac{\partial^2 v}{\partial x^2} + \frac{(1+\nu)}{2} \frac{\partial^2 v}{\partial x \partial y} - (1-\nu) S_0 \frac{\partial w}{\partial x} + \frac{p_y}{k} = 0$$

(13)

$$\nabla^2 \nabla^2 w - \frac{k}{D} [(1-\nu) S_0 (\frac{\partial v}{\partial x} + \frac{\partial v}{\partial y} - 2 S_0 w)] - \frac{p_z}{D} = 0,$$

$$k = \frac{Eh}{1-\nu^2}, \quad D = \frac{Eh^3}{12(1-\nu^2)}$$

$$S_0 = \frac{1}{L_{xy}} = \frac{\partial^2 z}{\partial x \partial y}$$



then boundary cond.

$$B_1 \frac{\partial^4 w}{\partial y^4} = D \left[\frac{\partial^3 w}{\partial x^3} + (2-\nu) \frac{\partial^3 w}{\partial x \partial y^2} \right]$$

$$B_2 \frac{\partial^4 w}{\partial y^4} = -B \left(\frac{\partial v}{\partial x} + \nu \frac{\partial v}{\partial y} - \nu w \right) \quad (14)$$

$$C \frac{\partial^3 w}{\partial x \partial y^2} = D \left(\frac{\partial^2 w}{\partial x^2} + \nu \frac{\partial^2 w}{\partial y^2} \right)$$

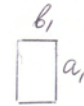
$$EF \frac{\partial^2 v}{\partial y^2} = B \frac{1-\nu}{2} \left(\frac{\partial v}{\partial x} + \frac{\partial v}{\partial y} - 2 S_0 w \right),$$

$$B_1 = EJ_1, \quad B_2 = EJ_2$$

$$C = \sigma \cdot \beta \cdot a \cdot b^3; \quad EF = E a \cdot b_1$$

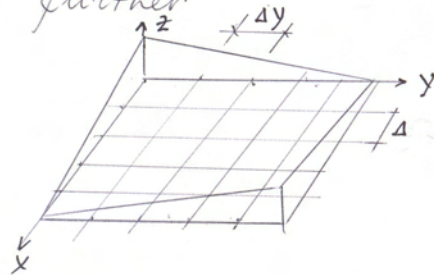
$$J_1 = \frac{b_1 \cdot a_1^3}{12}; \quad J_c =$$

$$\sigma = \frac{E}{2(1+\nu)}$$



$$\beta = f(a_1, b_1)$$

further



For example
 $f(x, y)$

derivations in finite differences

$$\frac{\partial f_k}{\partial x} = \frac{f_b - f_d}{2 \Delta x}$$

$$\frac{\partial^2 f_k}{\partial x^2} = \frac{f_b - 2f_k + f_d}{2 \Delta x^2}$$

$$\frac{\partial^3 f_k}{\partial x^3} = \frac{f_p - 2f_b + 2f_d - f_n}{2 \Delta x^3}$$

$$\frac{\partial^2 f_k}{\partial x \partial y} = \frac{f_f + f_h - f_c - f_g}{4 \Delta x \cdot \Delta y}$$

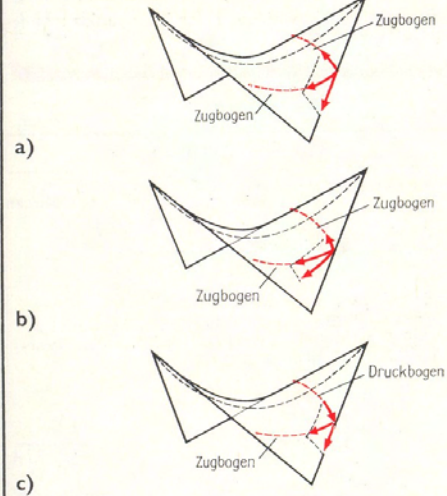
$$\frac{\partial^4 f_k}{\partial x^4} = \frac{f_n - 4f_d + 6f_k - 4f_b + f_p}{\Delta x^4} \quad \text{and so on}$$

with
 similar
 point

→ (13) → algebraic system
 if lin. Gauss → u, v, w → N, M
 a.s. on

Tragverhalten

HYPAR-Sattelflächen



Erläuterungen

Seilnetz

Unter gleichmäßiger verteilter Last in Richtung der z-Achse vereinigen sich die Kräfte am Rand zu resultierenden Kräften, die

- in Richtung des Randes verlaufen wenn im Seilnetz die Last zu gleichen Teilen von Zugbögen abgetragen wird

Wird die Last zu ungleichen Teilen von Zugbögen abgetragen, so

- verlaufen die resultierenden Kräfte am Rande schräg zum Rand in der jeweiligen Tangentialebene des Seilnetzes
- die Lasten lassen sich zerlegen in Kräfte in Richtung des Randes und in Kräfte quer zum Rand
- zu welchen Teilen die Last abgetragen wird, ist abhängig vom Asymptotenwinkel des HYPAR und von der Seilführung

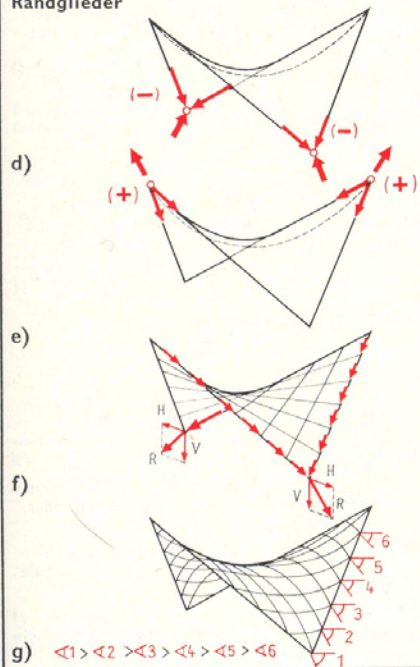
Schalen

Aus der gleichmäßig belasteten Hypar-Schale werden auf die Randglieder Zug- und Druckkräfte übertragen, die sich zu einer Resultierenden in Richtung der Randglieder vereinigen

Hinweis

Die relativ dünnen Schalen sind nur im begrenzten Umfang wegen der Beulgefahr zur Aufnahme von Druckkräften befähigt. Diese Beanspruchung ist mit entsprechenden Sicherheitsabstand unter der kritischen Beullast zu halten. Dies kann mit zusätzlich eingeleiteten Zugkräften, durch Verspannung, erfolgen

Randglieder



Abstützung an den Tiefpunkten:
Normalkraft $N = \text{Druck } (-)$

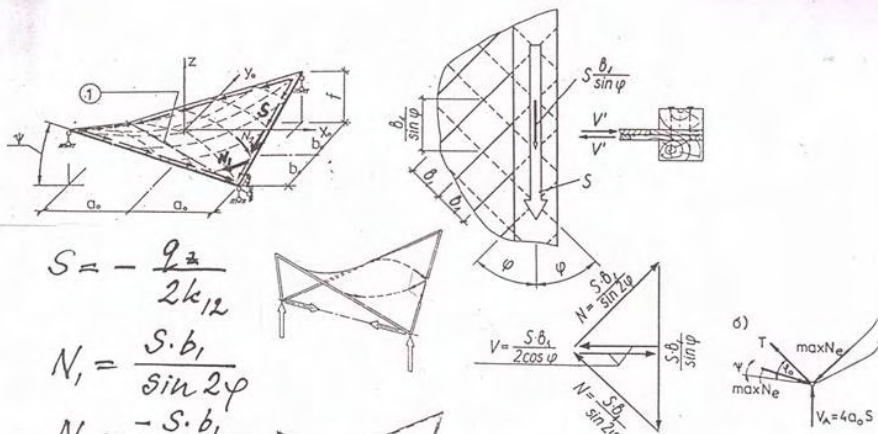
Abhängung an den Hochpunkten:
Normalkraft $N = \text{Zug } (+)$

Die Kräfte in Richtung des Randes nehmen zu den Auflagern hin zu. Sie werden von einer Randverstärkung, dem Randglied, als Längskräfte zu den Auflagern abgeleitet. Sie erzeugen im Randglied eine linear zunehmende Normalkraft N :

- am freien Ende = 0
- am Auflager = maximal

Randglieder sind knickgefährdet. Die Aussteifung kann durch die Schalenfläche oder durch ein Stabnetz in deren Tangentialebene erfolgen, hierbei ist zu beachten:

- die Änderung der Richtung der Aussteifung infolge stetiger Änderung der Neigung der Tangentialebene
- elastische Bettung des Randgliedes durch Schale oder Stabnetz



$$S = -\frac{q_z}{2k_{12}}$$

$$N_1 = \frac{S \cdot b_1}{\sin 2\psi}$$

$$N_2 = -\frac{S \cdot b_1}{\sin 2\psi}$$

$$V' = \frac{S \cdot b_1}{2 \cdot \cos \psi}$$

$$\max N_e = \frac{2a_0 S}{\cos \psi}$$

$$T = 4a_0 \cdot S \cos \psi_0$$

$$V_A = 4a_0 S \tan \psi$$

$$(N_1 = \frac{S b_1 x_1}{\sin 2\psi}$$

$$N_2 = -\frac{S b_1 x_2}{\sin 2\psi}$$

$$x_1 = \frac{1}{1 + \frac{A_2}{A_1}}; x_2 = 1 - x_1)$$

For example: $a_e \times a_e = 2a_0 \times 2a_0 = 12 \times 12 \text{ m}$,
 $a_0 = b_0 = 6 \text{ m}$, $q_z = 25 \text{ kN/m}^2$,
 $f = 24 \text{ m}$, $\psi = 11,3^\circ$, $\psi_0 = \varphi = 45^\circ$
 $b_1 = 150 \text{ mm}$

$$k_{12} = \frac{f}{2a_0^2} = 0,0333$$

$$S = -37,5 \text{ kN/m}, N_1 = 5,63 \text{ kN}, N_2 = -5,63 \text{ kN}$$

$$V' = 3,98 \text{ kN}, \max N_e = 458,9 \text{ kN}, T = 636,4 \text{ kN}$$

$$V_A = 180 \text{ kN}$$

$$\text{Stability } p_{cr} = \frac{2ET^2 \cdot f^2}{\sqrt{3} a_e^2 b_e^2}$$

$$E = 3000 \dots 6000 \text{ MPa}$$

$$(\nu = 0,4 \dots 0,7).$$

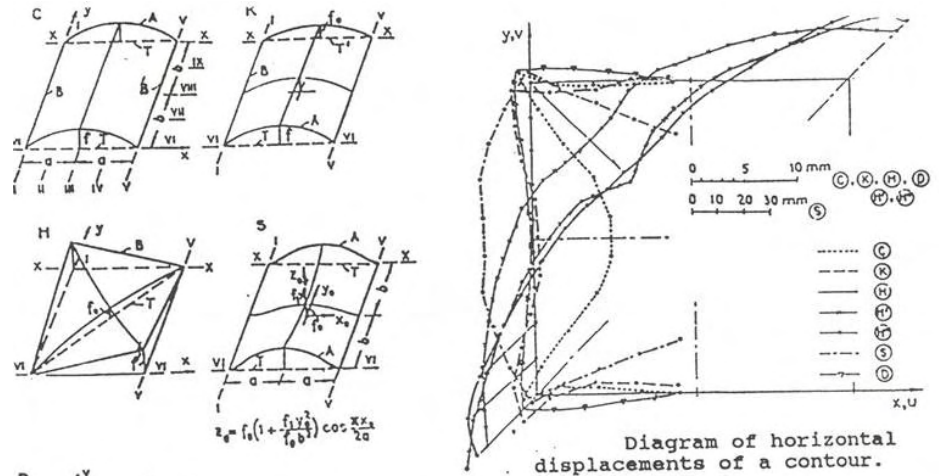
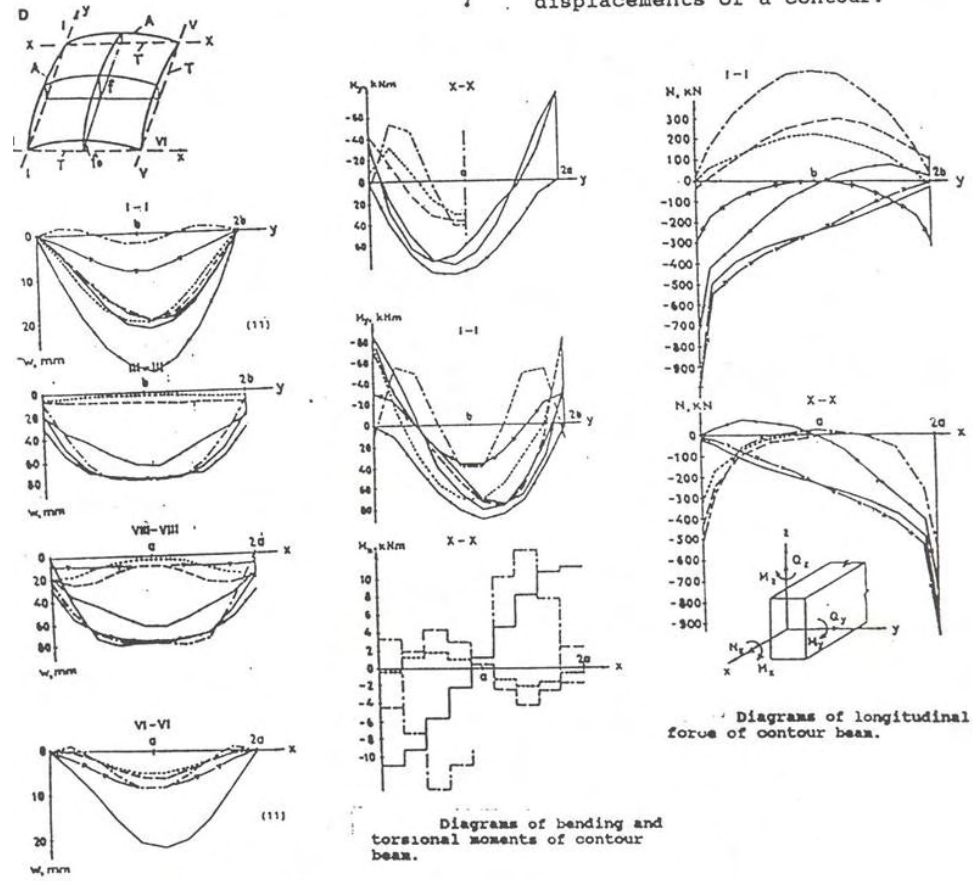


Diagram of horizontal displacements of a contour.



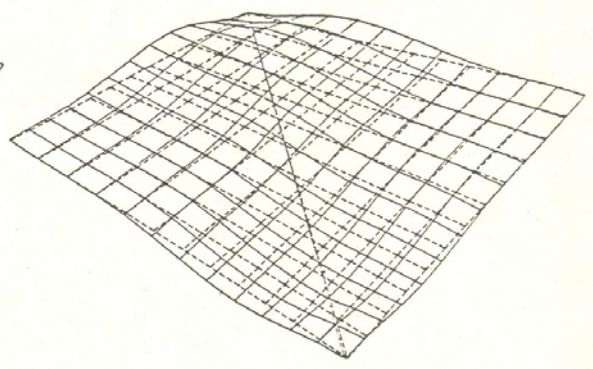
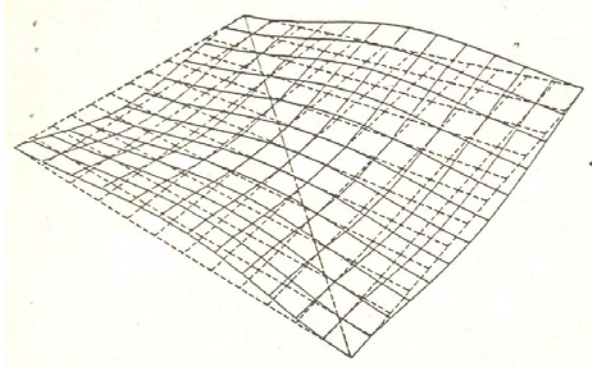
Diagrams of bending and torsional moments of contour beam.

Diagrams of vertical

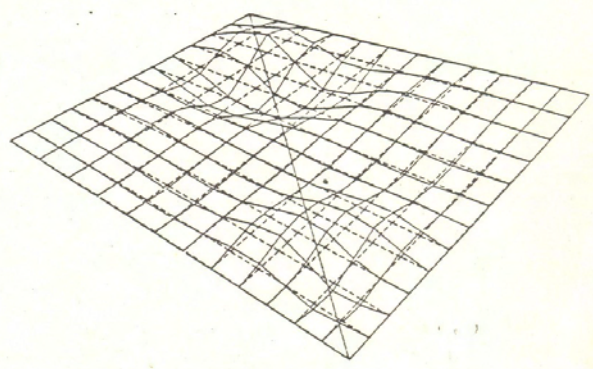
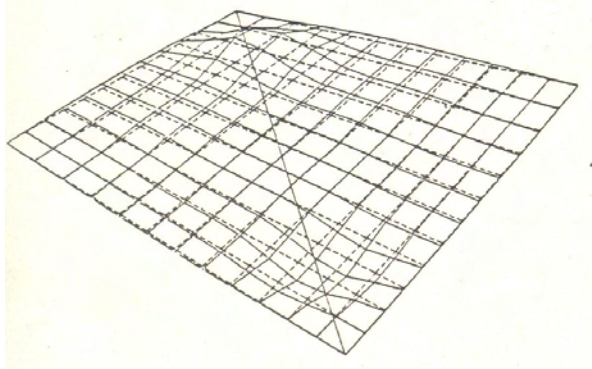
Diagrams of longitudinal force of contour beam.

$\lambda > 1.3$

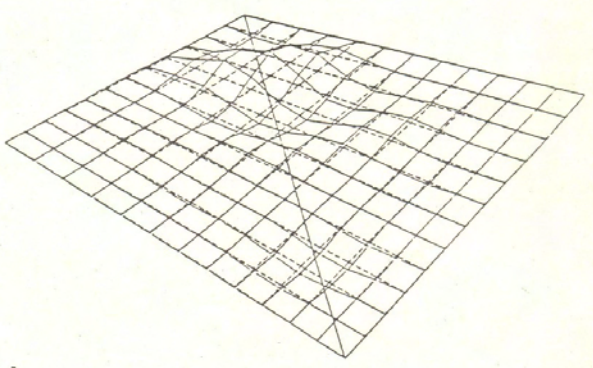
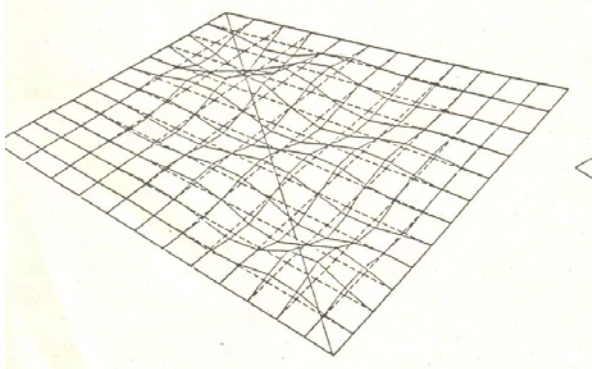
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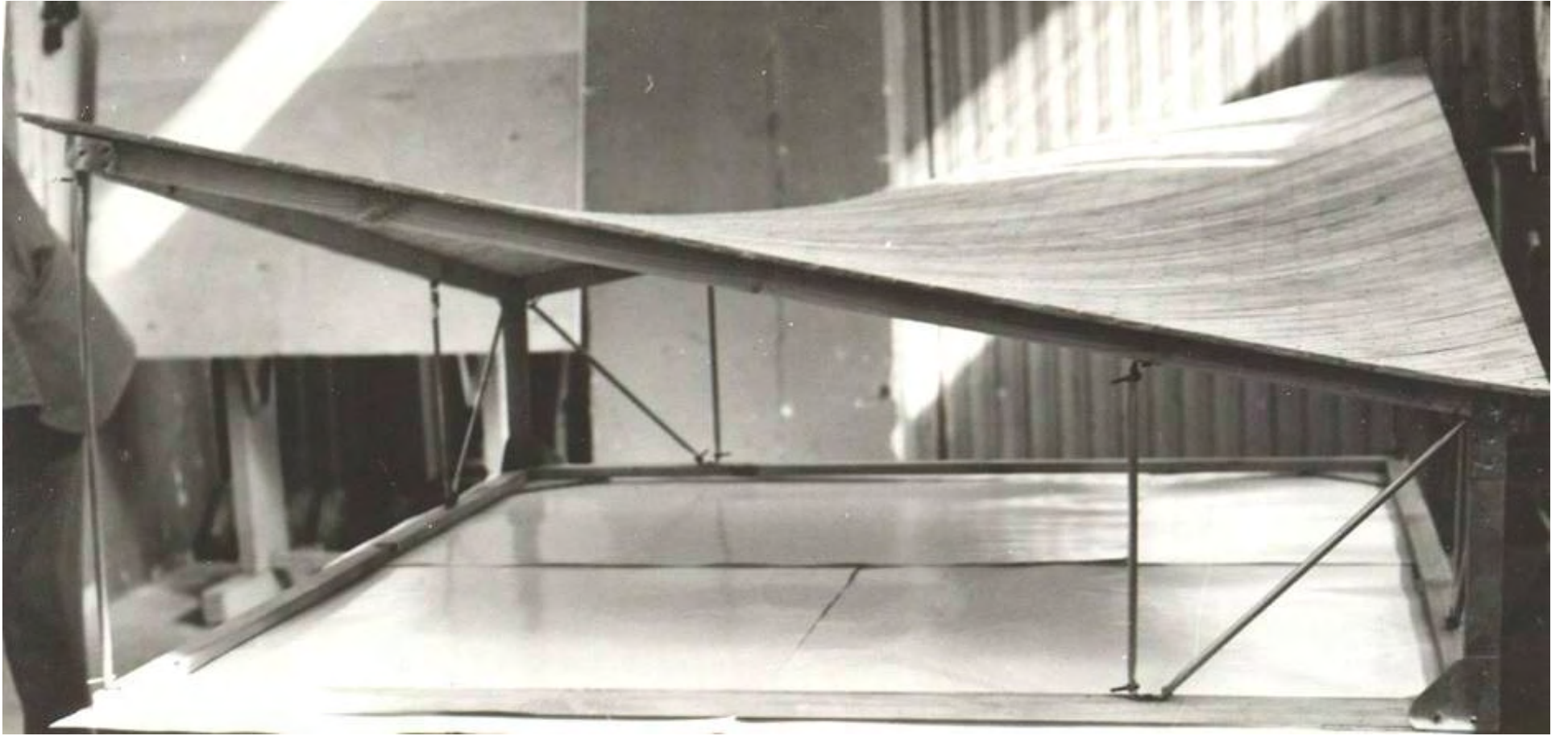


$\lambda = 0.8 - 1.3$



$\lambda < 0.8$

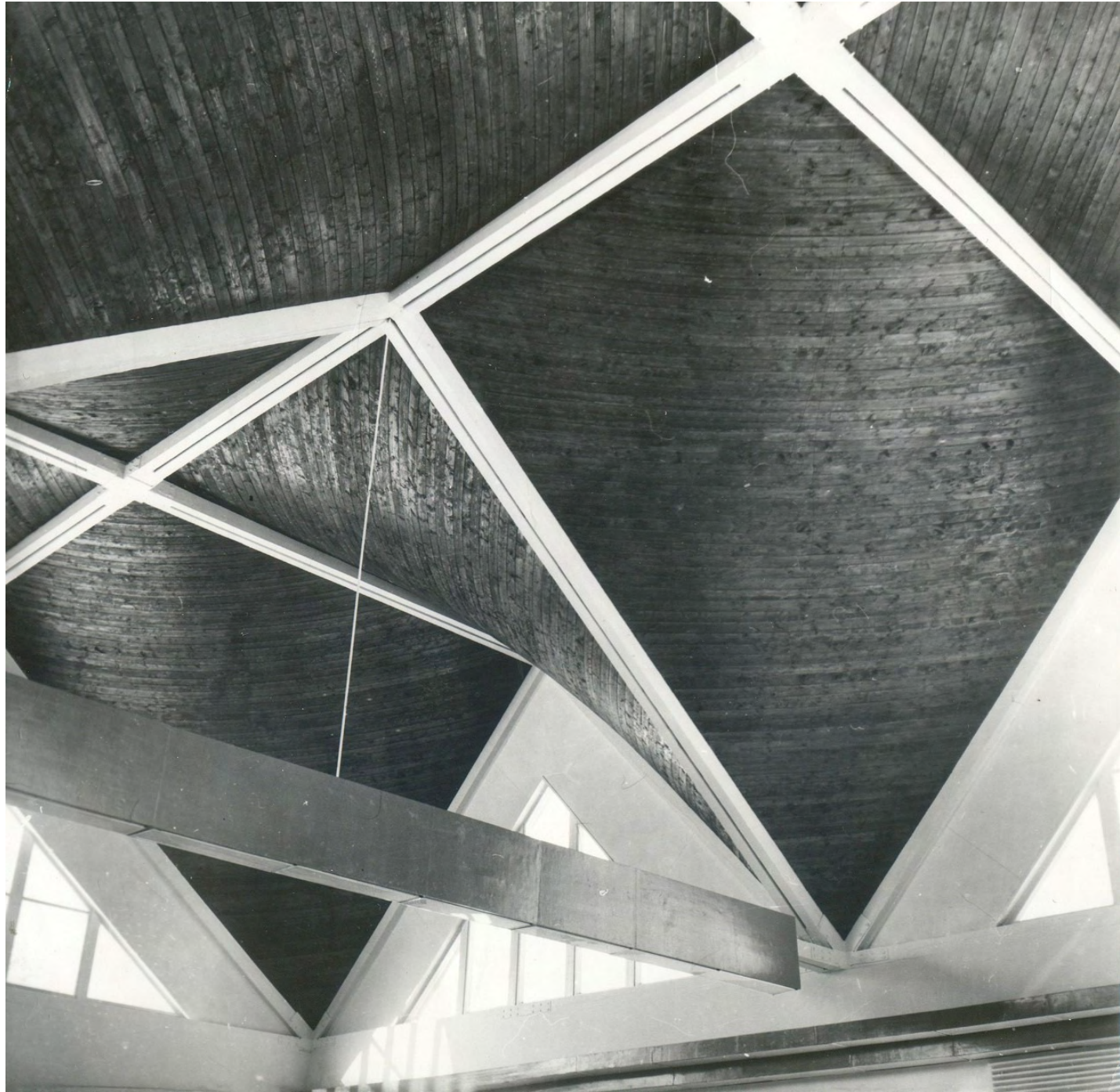




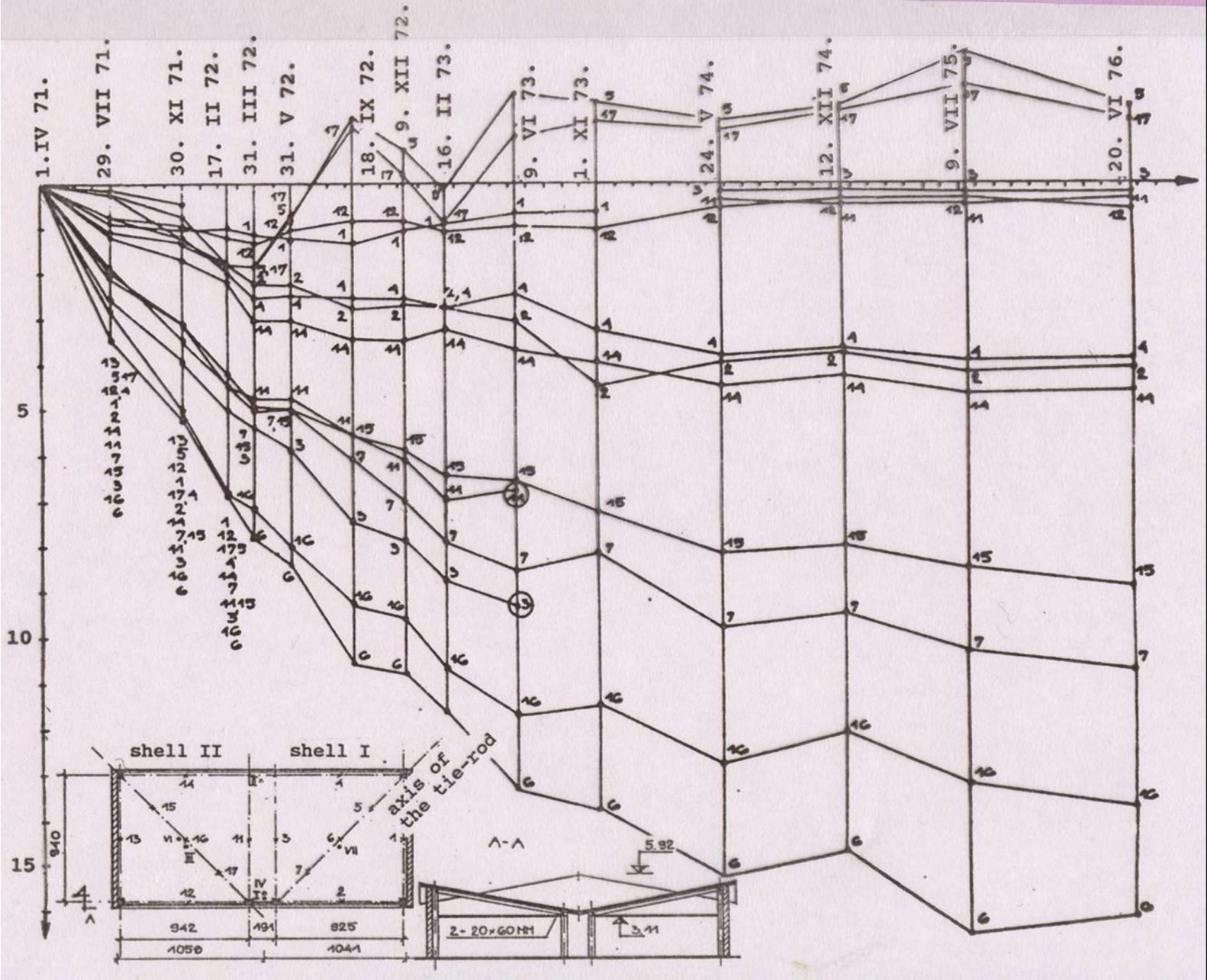


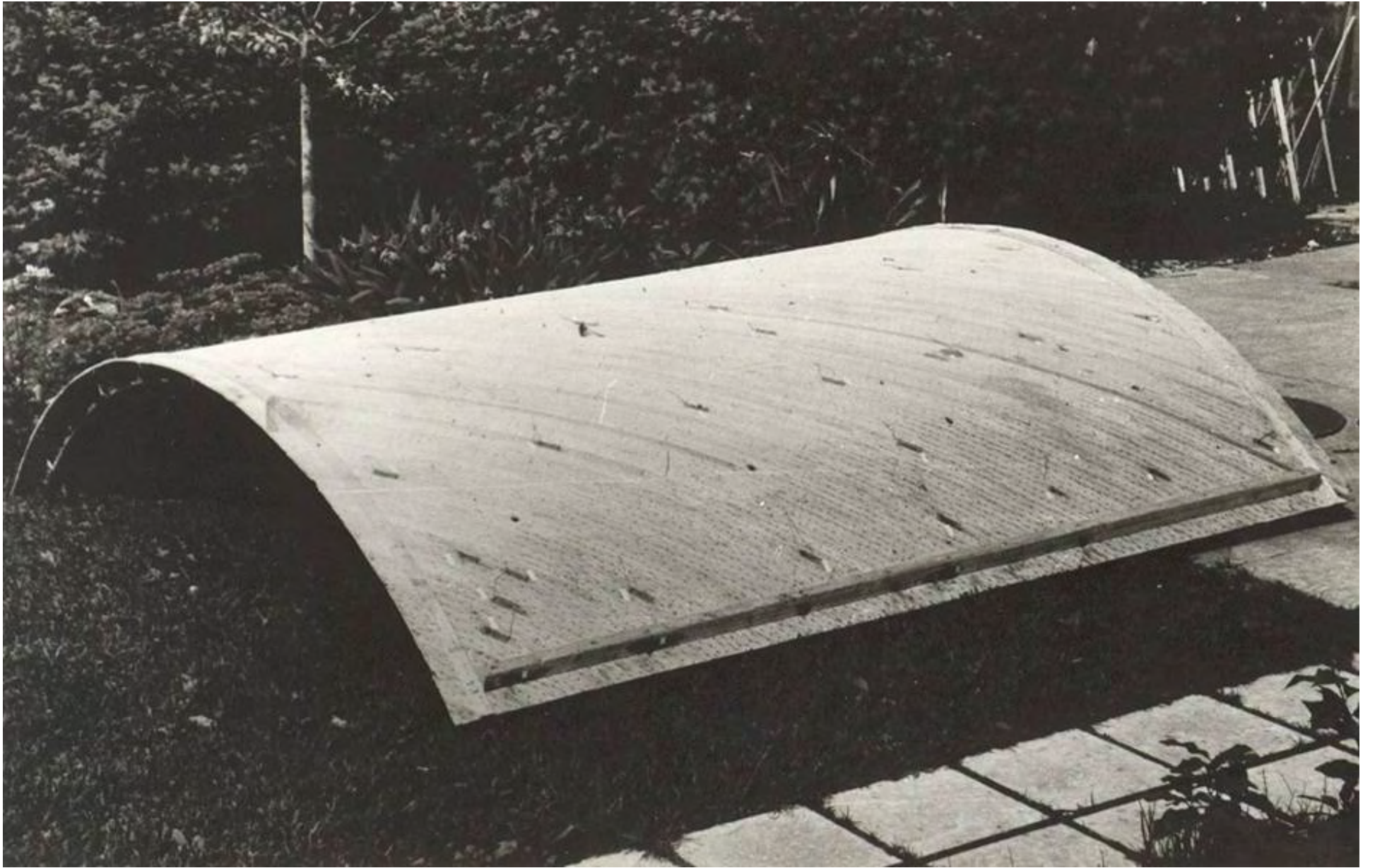














NÄGELD $\varnothing 4 \dots 6 \text{ mm}$, $L = 180 \dots 220 \text{ mm}$.

ARVUTUS:

- 1) PIKISUUNALISED NORMAALJÕUD N_1 VÕET. VASTU DIKISUUNALISE LAUDISE JA ^{SELLE} VÕRRA TUGE-ROUSE POOLT;
- 2) NIKKEJÕUD T - KATEKORDSE KALDLAUDISE POOLT;
- 3) PÕIKSUUNAS MÕJUVAD $M_2 \approx N_2$ - RIBIDEGA, (KOORIKUT EI ARVEST).

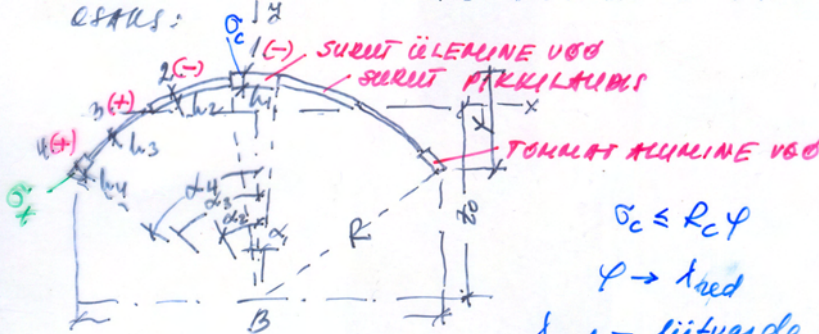
KATSELISELT ON MÄÄRATUD, ET RIBIVOLUKOORIKUT VÕIB ^{SÜMM. KOORMISE PÜKK} ~~KA~~ ^{SELLE} ~~KA~~ ^{SELLE} MITTEDEF. PÕIKLÕIKEGA TÄL-
KUI VÄRIB ^{SAITUS}

$$J_r \geq \frac{S_r B^2}{4 \cdot 10^6} \quad ; \quad J_r - \text{RIBI 2N. MOM.} \\ S_r - \text{RIBIDE SAHM.}$$

MITTESÜM. KOORMISE PÜKK ARVUT. VÄTTA-
VALT ET. MEH. REEGLITELE.

ARVUTUSTES VÕIB PÕIKLÕIKE JÄÄT 4-K)

OSAKS:



$$\sigma_c \leq R_c \varphi$$

$$\varphi \rightarrow \lambda_{red}$$

$$\lambda_{red} - \text{liitvanda } d \rightarrow \lambda_{ef}$$

$$\lambda_{ef} = S_r$$

$$\sigma_t \leq R_p \cdot m - \text{arvest na nõrgestatud pöstrude}$$

JURUTUD KALDLAUDADELT LAUDIS KONTROLLIT.

ÜHEAEGSELT SURVELE JA PÄENDELE, KUI

$$M = D_c \cdot \varphi_1$$

SURUTUD
KALDLAUDISE
SURVEJÕUD

φ_1 - KALDLAUDISE KÕVERUSINGOL DIKRUVEL S' , M.S

VÄRDNÄ NÄELTE VÄHEKAUGUSEGA KALDSUMISEL VABADIKKUSEKS VÕET 0,6 S'

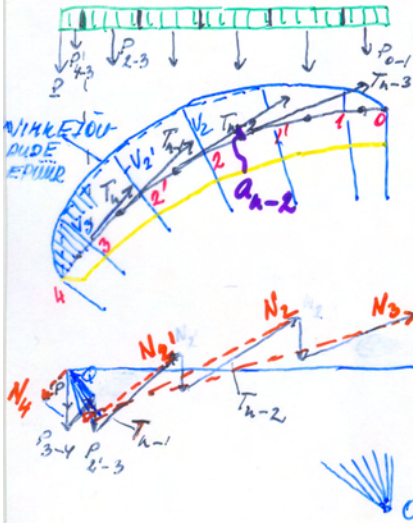


VÄHEKAARDED JA ROOVID ARVUT. MONTA 21 KOORMUSTELE.

KOORIKU RIBIS (KAARES) M JA IN, KUS RIBI KOORMUSTEKS 1) ΔQ - SEE ON POIKJOUUDE JUURDEKARU RIBIDE VÄHEL (NIHKEJÕUD) 2) V - REAKTIIVSED JÕUD RIBI JA KOORIKU VÄHEL (PÕLVITAJA RIBIDE VÄHEL) SUMMA RIBIDE VÄHEL



GRAAFILISELT:



P - AÄREKOORMUS; P_{4,3} - VÄLISEKS LÕIGUDE KÕRGE

N - RIBI SURVEJÕUD

T - LÕIGU ULATUMES V RESULTANT, KN

SÜMM. VERT. KOORMUSE PÕLVITAJAL:

$$V = \frac{\Delta Q_x \cdot S_x}{J_x}$$

HOR KOORMUSE PÕLVITAJAL

$$V = \frac{\Delta Q_y \cdot S_y}{J_y} \quad \frac{KN}{m}$$

KOSOSÜMMETRIILISE KOORMUSE PÕLVITAJAL

$$V = \frac{\Delta M_D \cdot S_w}{J_w}$$

KUS, J_x, J_y - IN. MOM x ja y suhtes
S_x, S_y - STAAT MOM - u
ΔM_D - VÄÄNEMOM JUURDEKARU (2) PIKKUSEL
J_w, S_w - SEKTORIAALNE JN. ja STAATMOM.

RIBI ARVUT. NENDE KOORMUSTEGA KUI TÄÄR. SÜSTEEM, MIDA VÕIB TEHA GRAFO-ANALÜÜSILISELT:

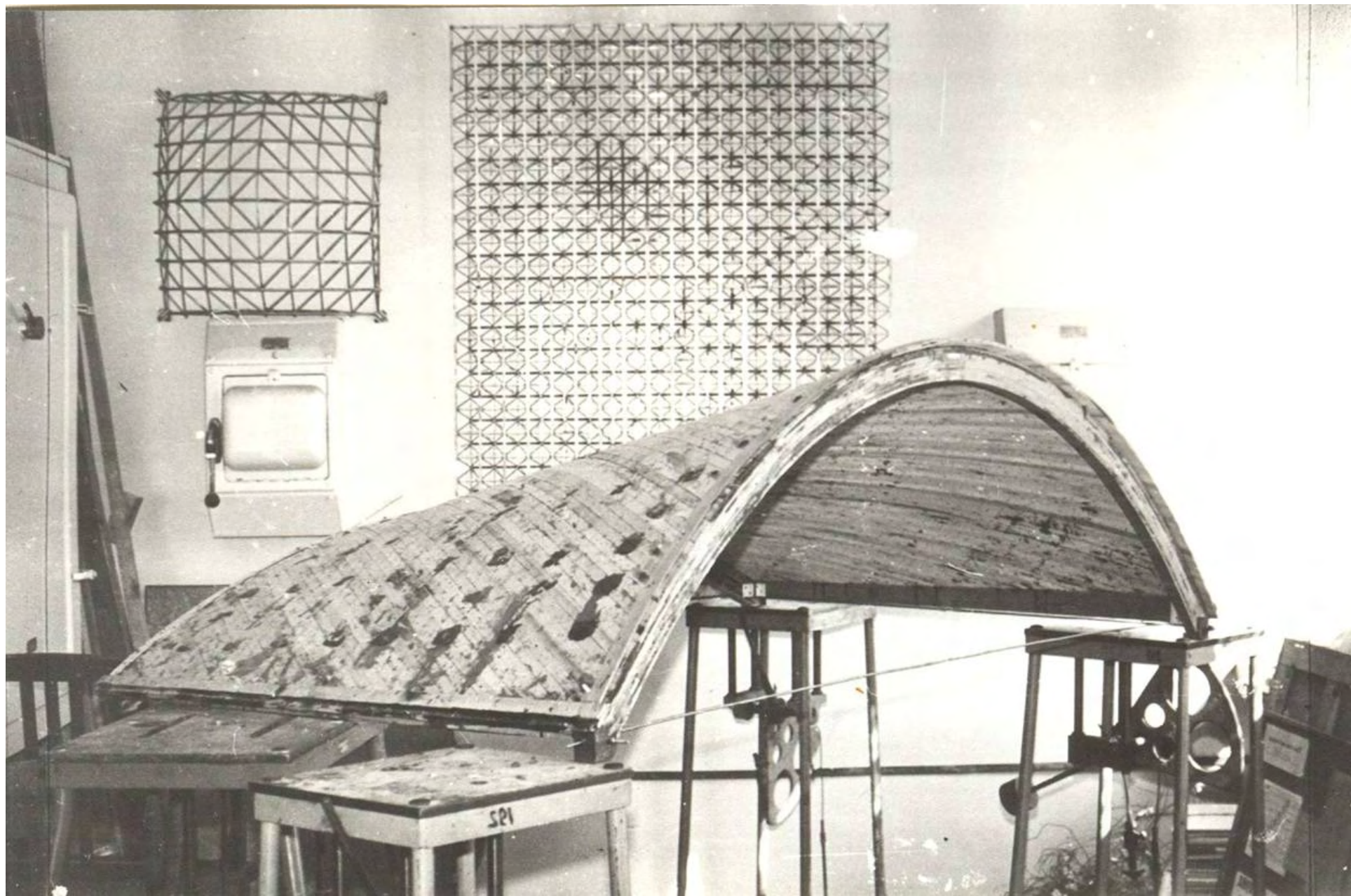
- RIBI VÄLISEERN JAOT USPEKS
- LEIT. VASTAVA OJA V RESULTANT T.
- MITTAHES PUNKTI (POIKLOIKE) M LEIT. KÕIGI ÜHELPOOL LÕIGET MÕJUVATE T JA VÄLISEJOUUDE M SUMMANA:

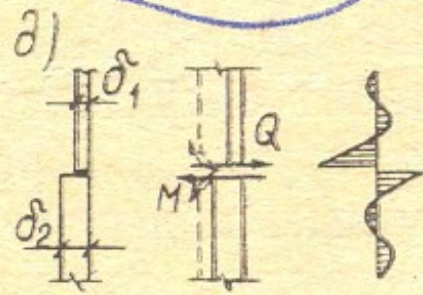
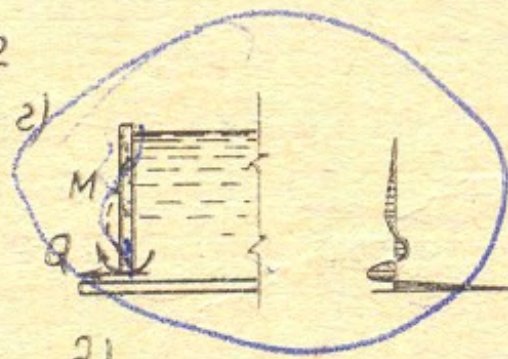
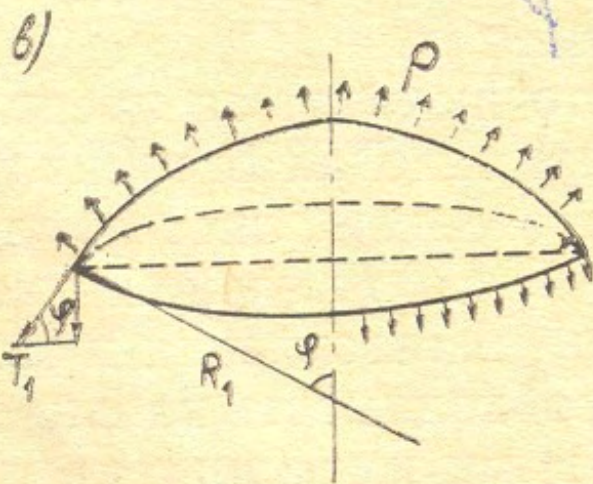
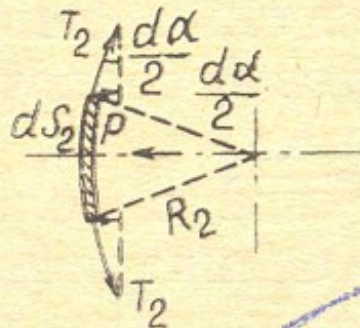
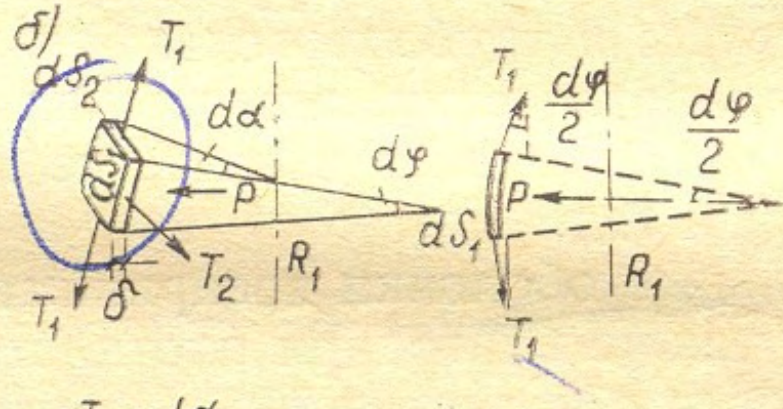
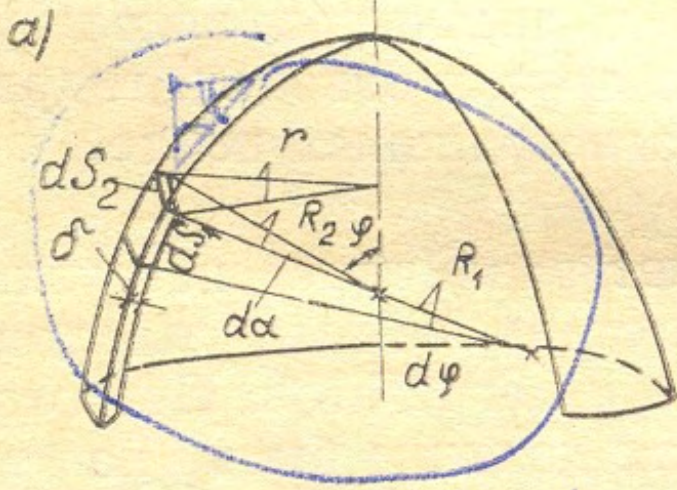
$$M = T_n \cdot a_n + T_{n-1} \cdot a_{n-1} \dots + T_0 \cdot a_0 \quad \text{- välisj. mom. öla.}$$

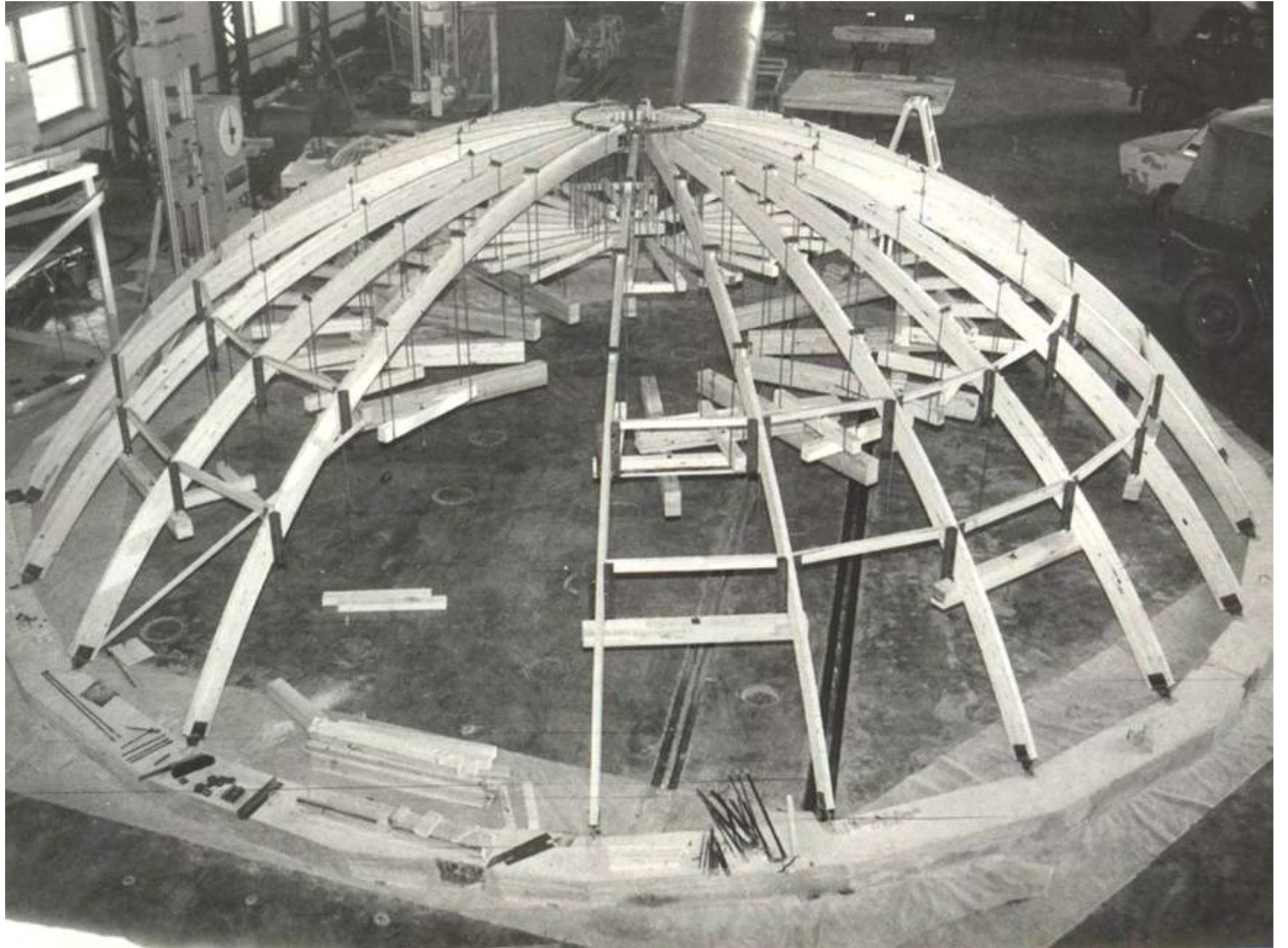
NORMAAL-(N) JA POIKJOUUDE Q MÄÄRA MISEKS LÕIGUDES LÜDET KÕIK VÄLISE JA NIHKEJÕUD ÜHELPOOL LÕIGET NING PROJEKT. VASTAVA PUNKTI PÕLVITAJA SUUNALE → N; SELLES PUNKTIS NORMAALI SUUNALE → Q.

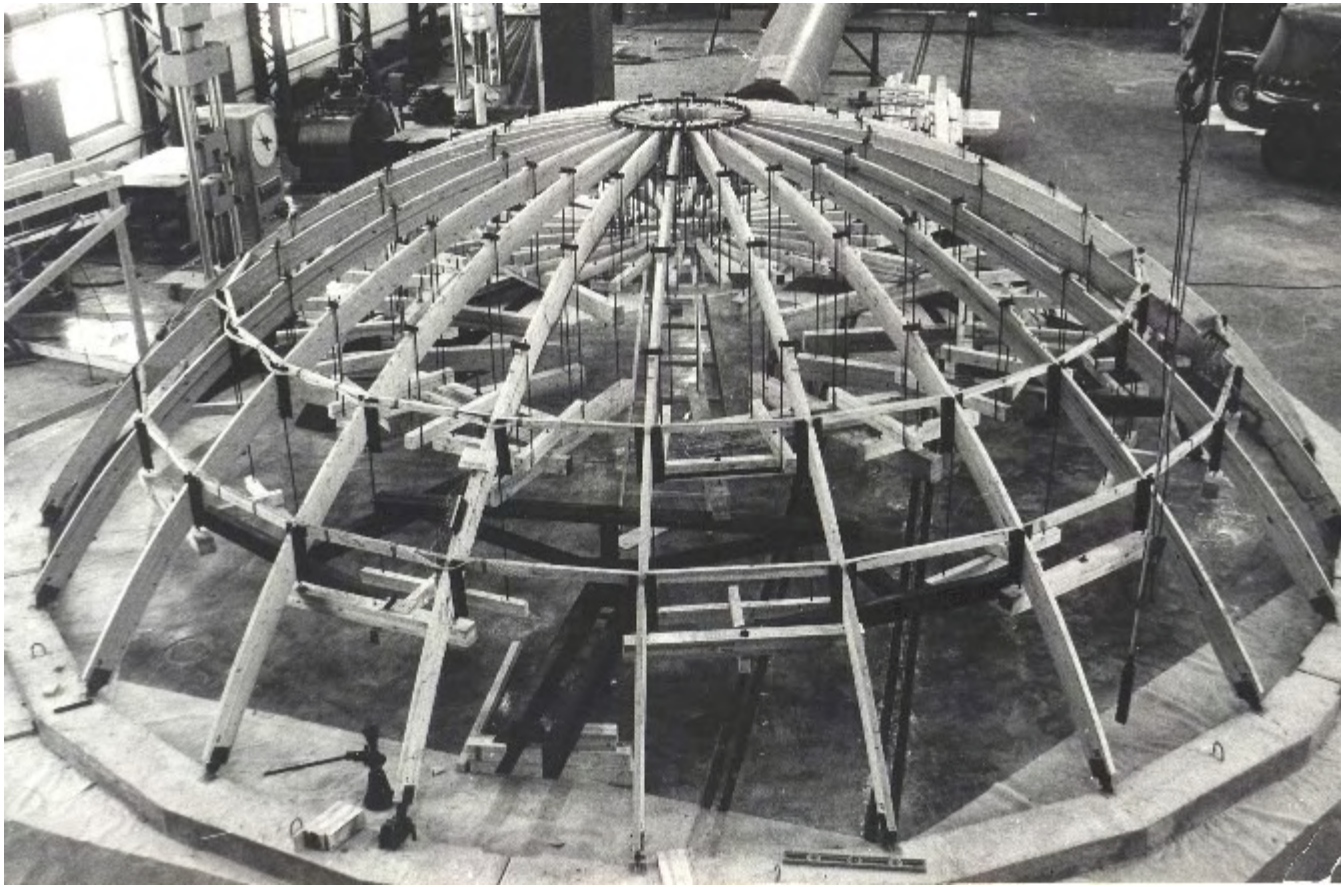
- RIBI POIKLOIGE VÄLIT JA DIM. NÄGU VASTAVA LÜTTALA POIKLOIGE (NÄELUTALA) PL.
- KOORIKUT RIBILE KINNIT NÄELTE ARV VASTAVALT T_i - le. (V - le)
- OTTAPÄINAD ARVUT. KUI PLAADID;
- VOLVKOORIKUTELE TULEKI ANDA EELTÖUS $f = \frac{l}{200}$

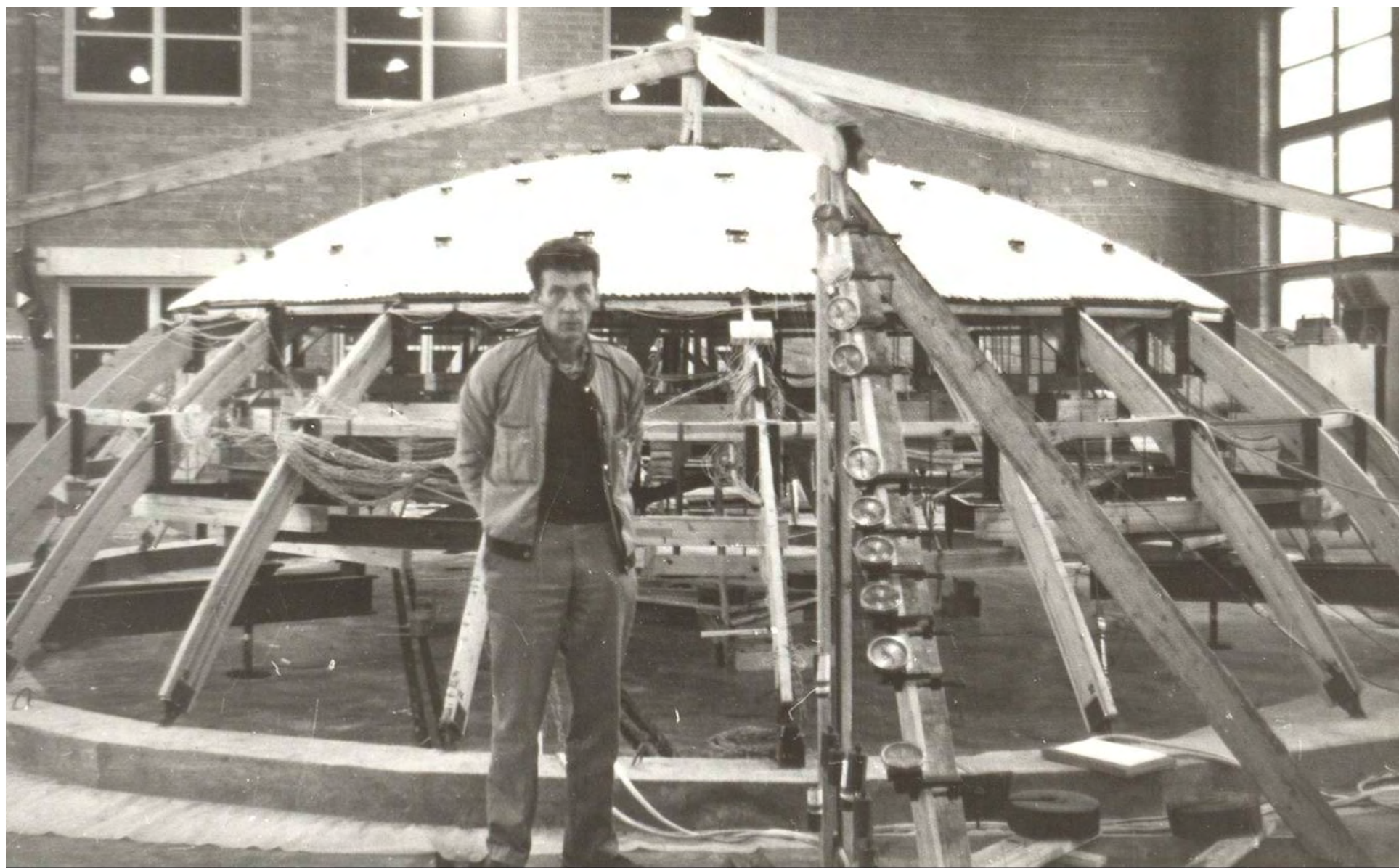




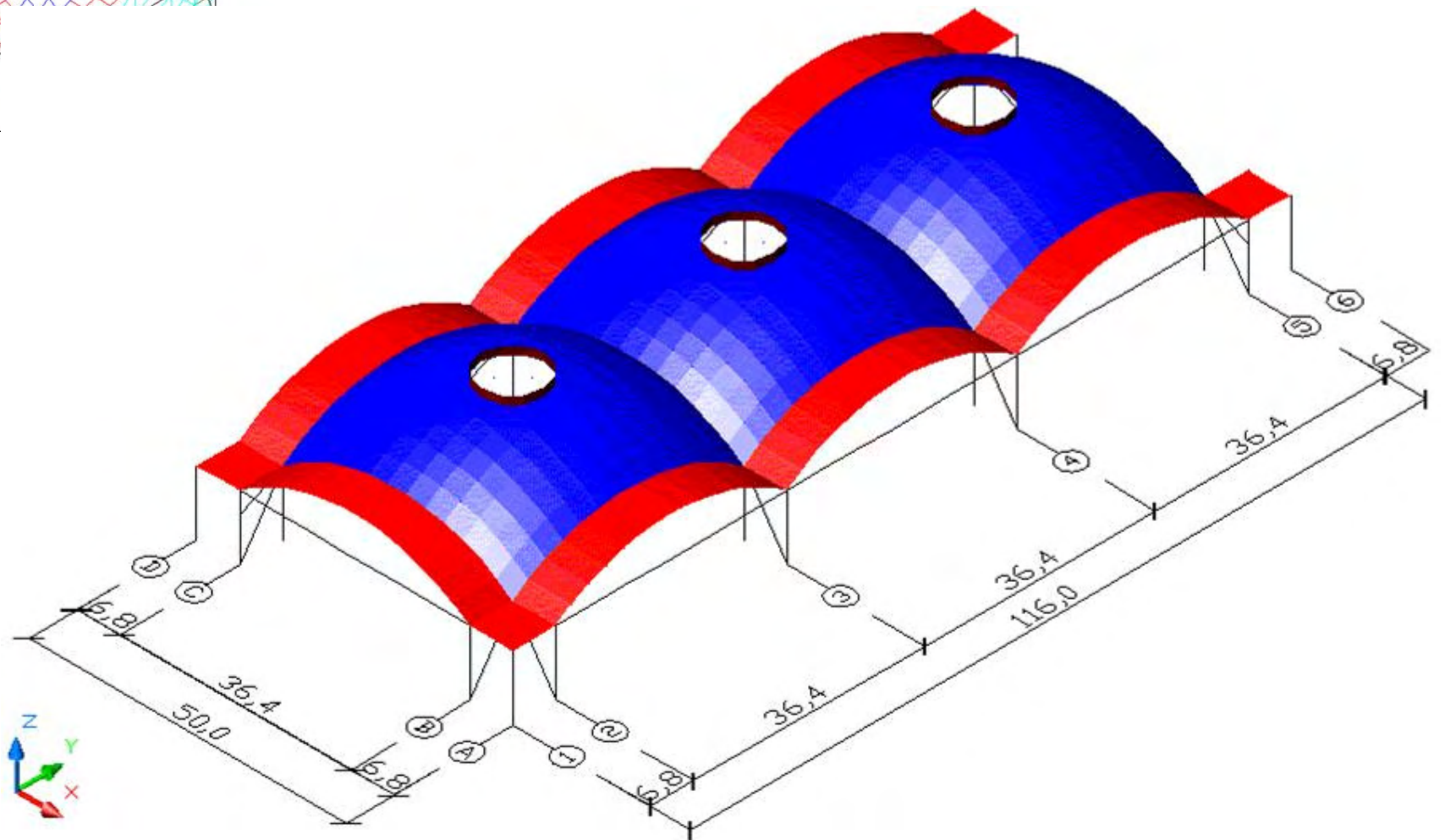
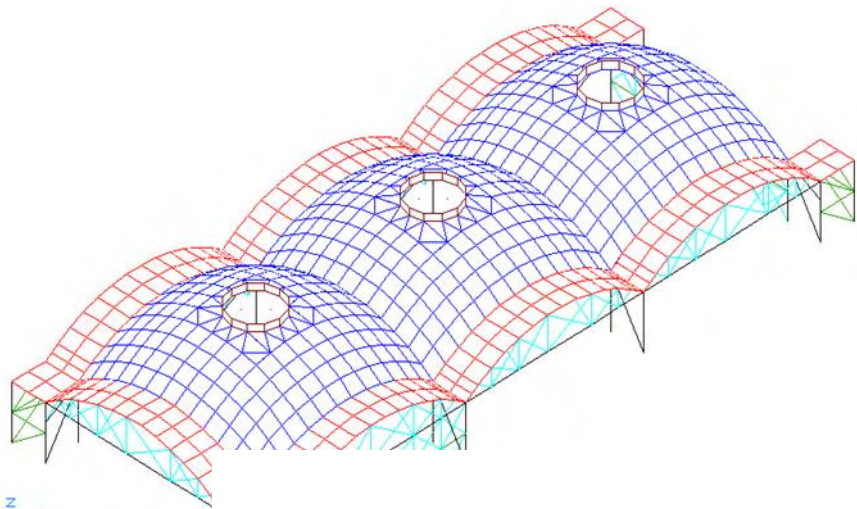


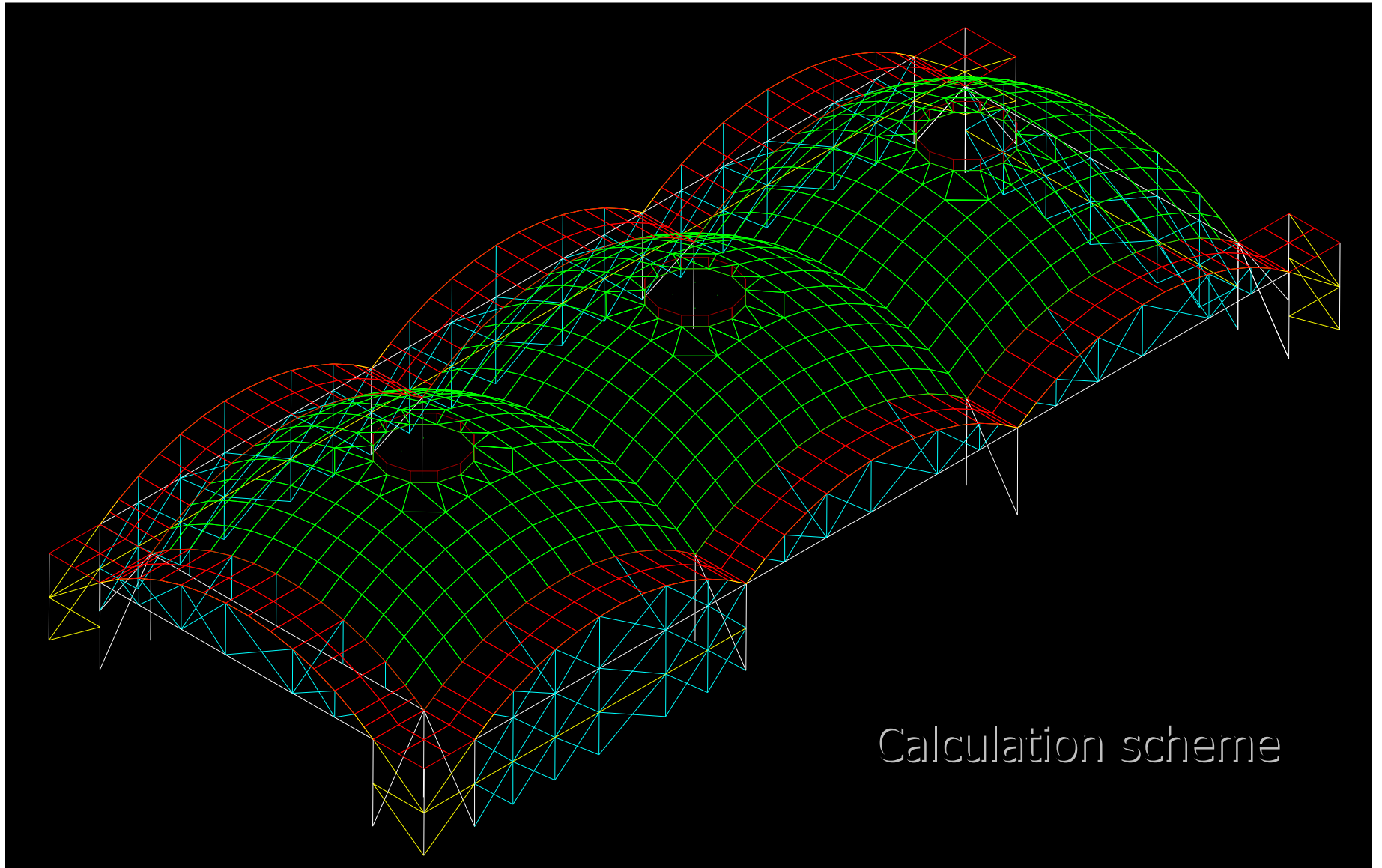












Calculation scheme

Contour

Node

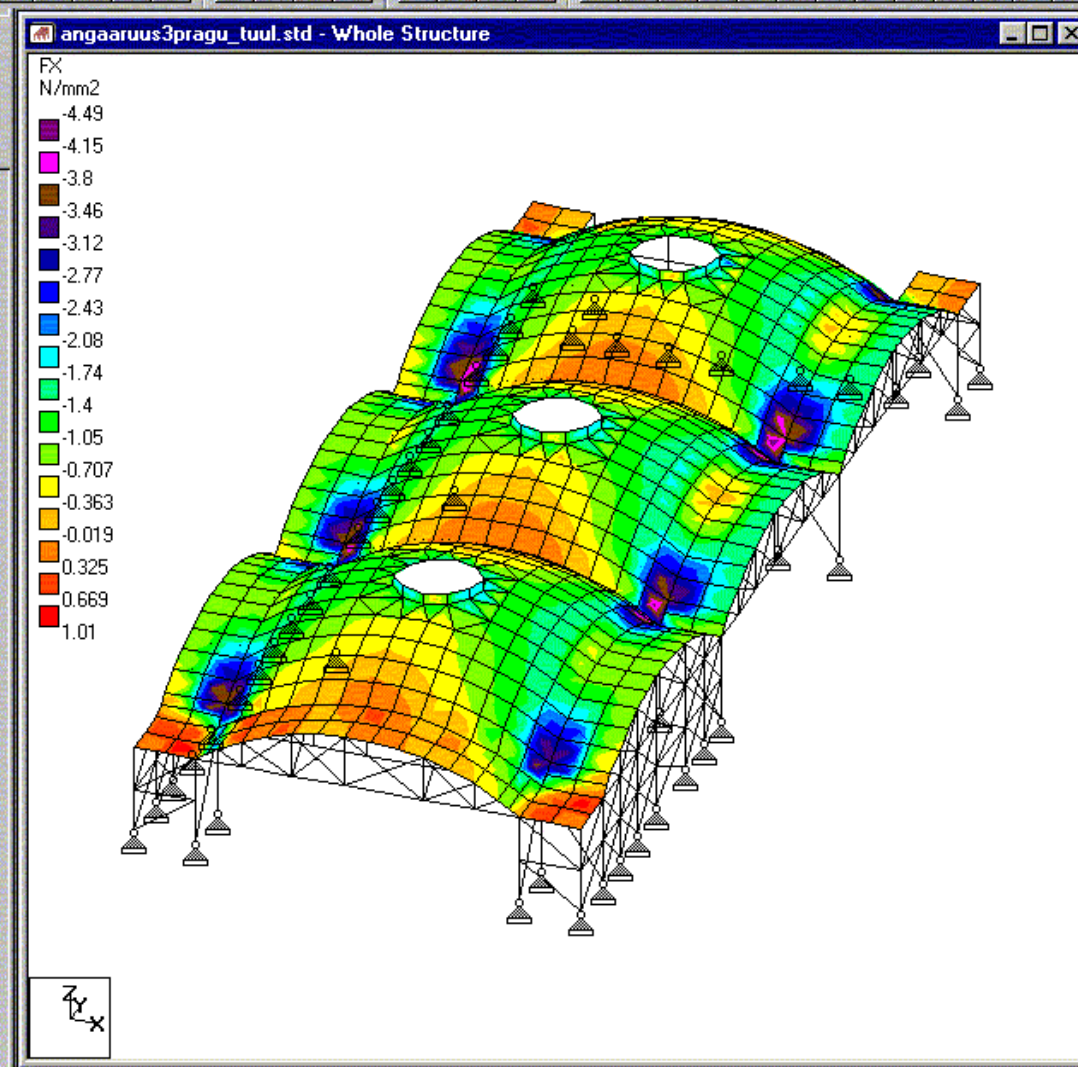
Beam

Plate

Slab

Animation

Reports

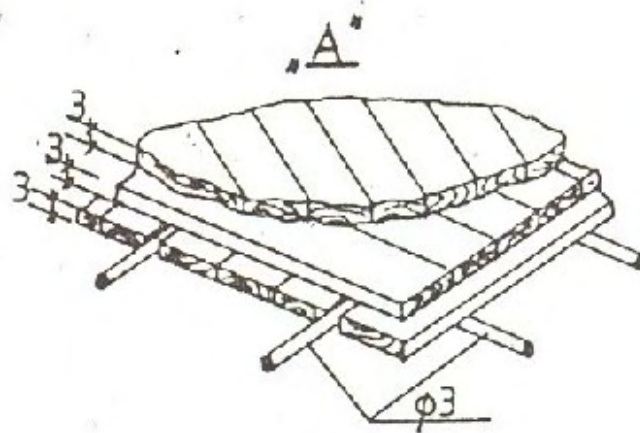
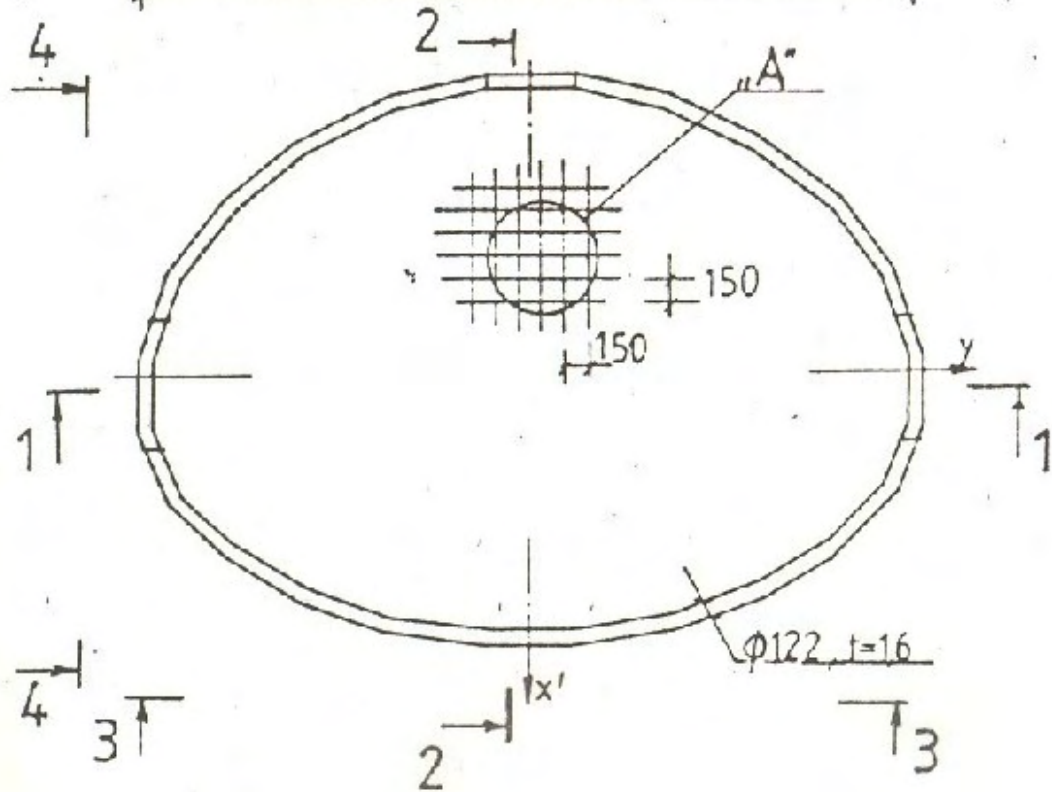
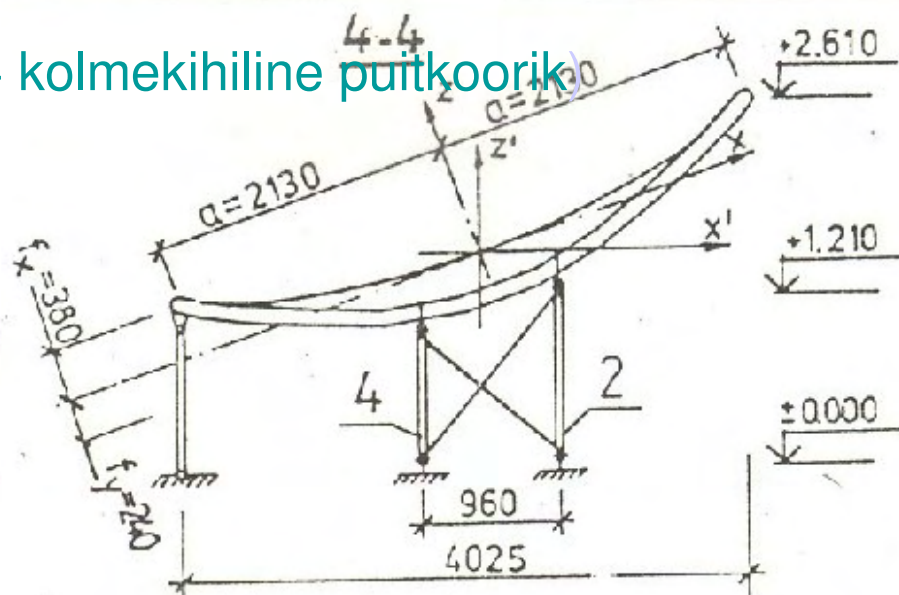
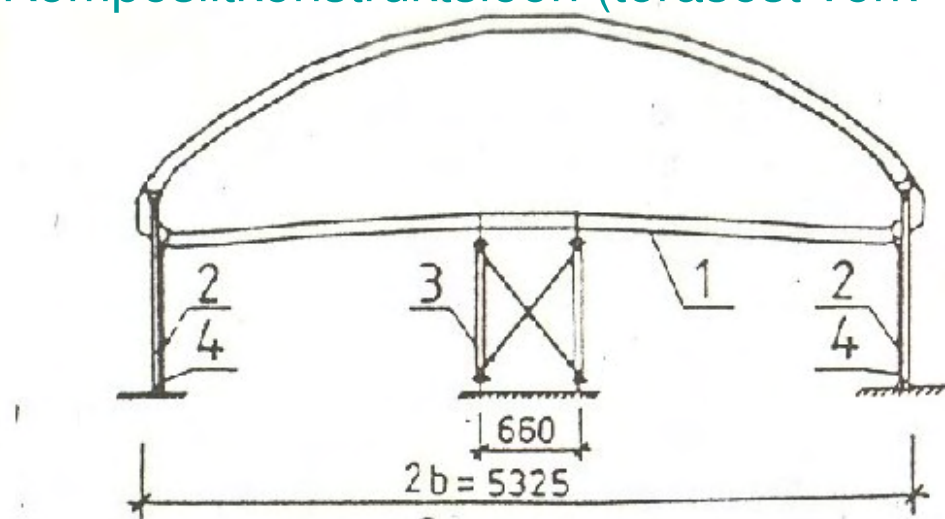


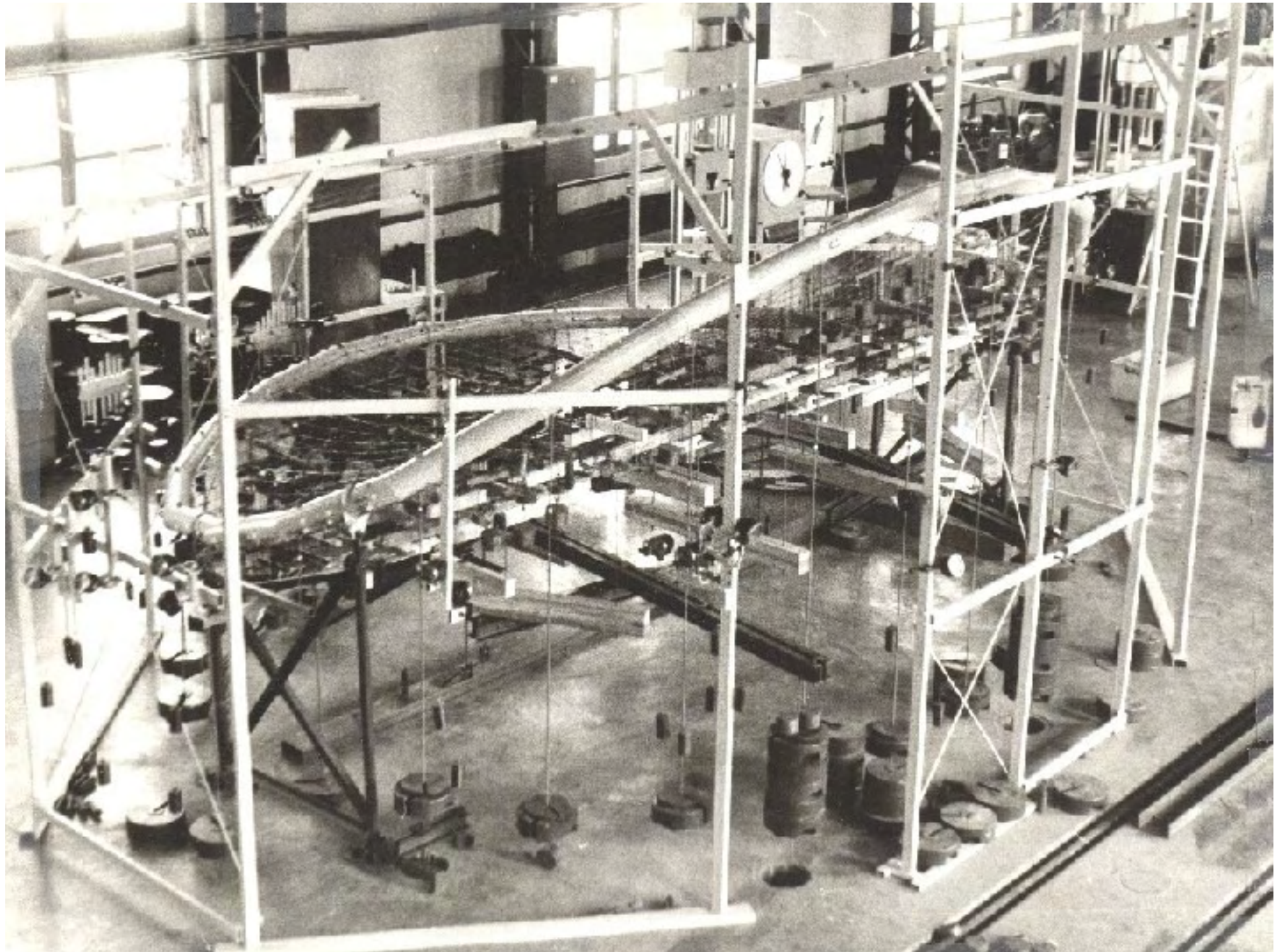
angaarus3pragu_tuul.std - Plate C...

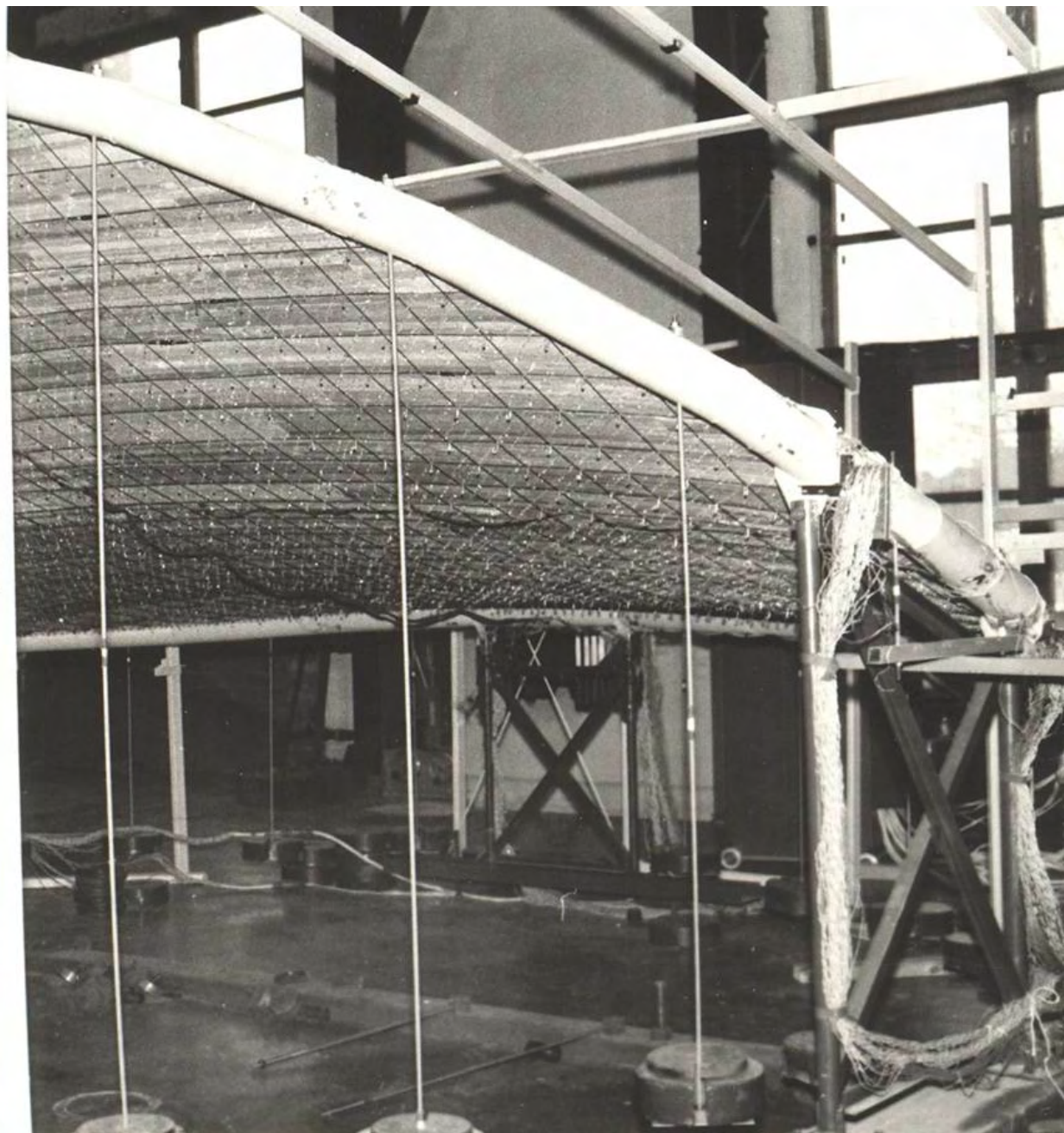
Shear, Membrane and Bending / Summ...

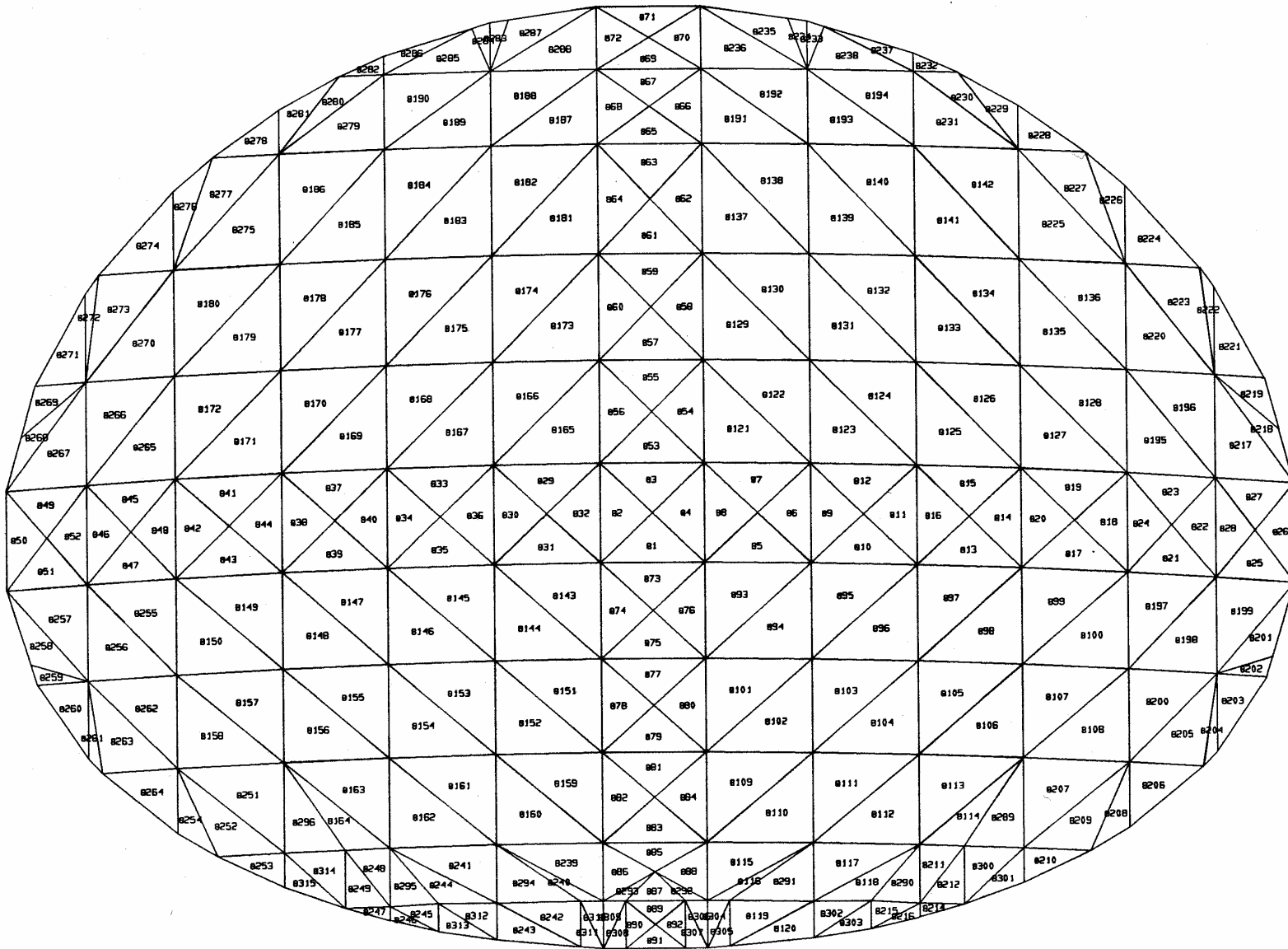
Plate	L/C	Shear	
		Qx N/mm2	Qy N/mm2
530	24 OMAKAAL	0.004	-0.015
531	24 OMAKAAL	0.004	0.019
532	24 OMAKAAL	0.000	0.009
533	24 OMAKAAL	-0.003	0.014
534	24 OMAKAAL	0.012	-0.011
535	24 OMAKAAL	0.001	0.021
536	24 OMAKAAL	0.017	-0.015
537	24 OMAKAAL	-0.016	-0.018
538	24 OMAKAAL	-0.002	0.018
539	24 OMAKAAL	0.002	0.017
540	24 OMAKAAL	0.002	0.011
541	24 OMAKAAL	-0.001	0.011
542	24 OMAKAAL	-0.015	-0.081
543	24 OMAKAAL	-0.031	0.126
544	24 OMAKAAL	0.023	0.001
545	24 OMAKAAL	-0.037	0.070
546	24 OMAKAAL	-0.006	0.018
547	24 OMAKAAL	0.003	0.022
548	24 OMAKAAL	-0.010	-0.006
549	24 OMAKAAL	-0.014	-0.011
550	24 OMAKAAL	-0.016	-0.020
551	24 OMAKAAL	-0.030	-0.026
552	24 OMAKAAL	-0.034	-0.034
553	24 OMAKAAL	-0.062	-0.057
554	24 OMAKAAL	-0.006	0.008
555	24 OMAKAAL	0.031	-0.056
556	24 OMAKAAL	0.010	0.006
557	24 OMAKAAL	0.002	-0.010
558	24 OMAKAAL	0.000	-0.008
559	24 OMAKAAL	-0.008	-0.005
560	24 OMAKAAL	-0.011	-0.004
561	24 OMAKAAL	-0.010	-0.001

Komposiitkonstruktsioon (terasest võrk + kolmekihiline puitkoorik)



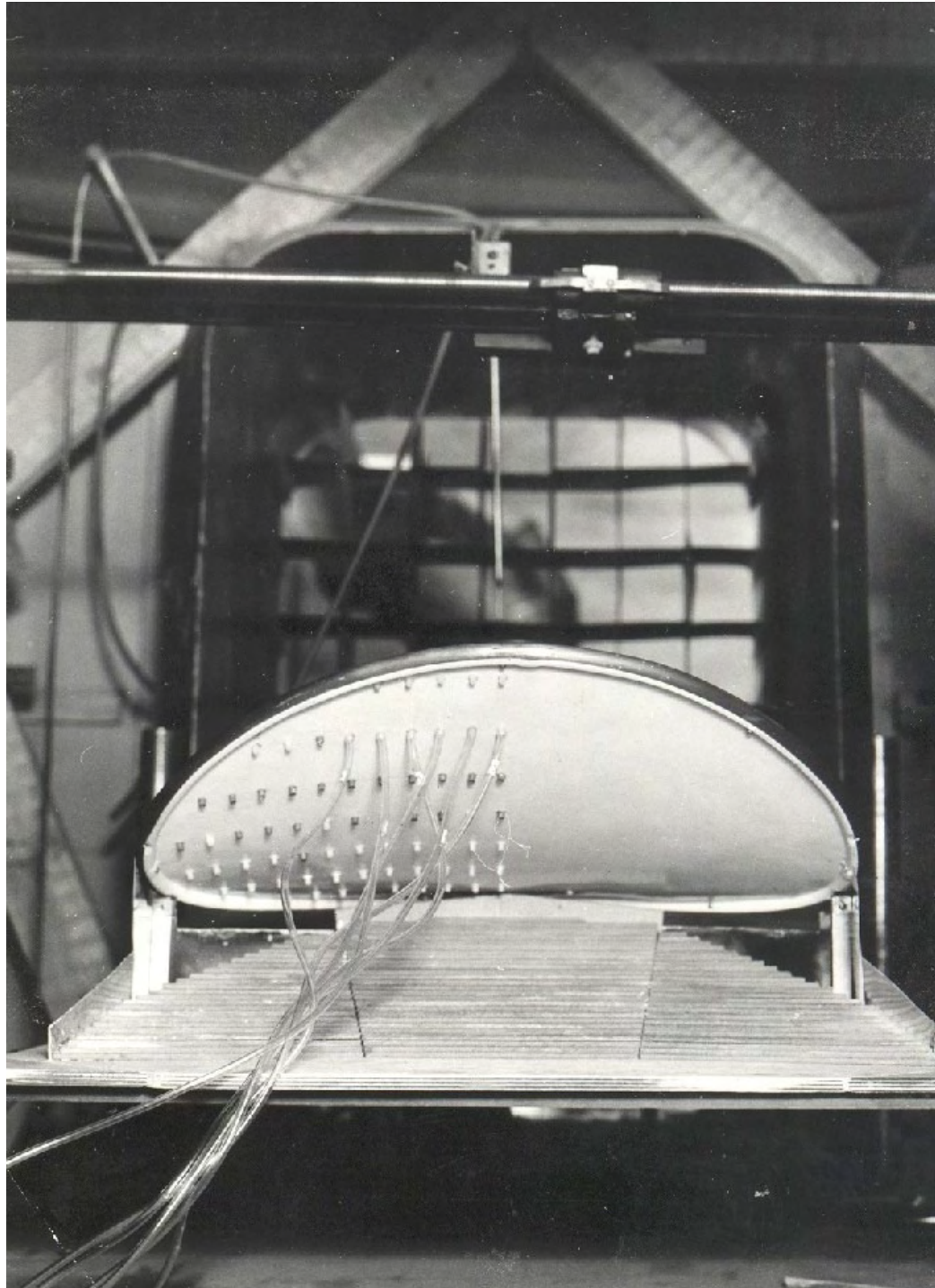


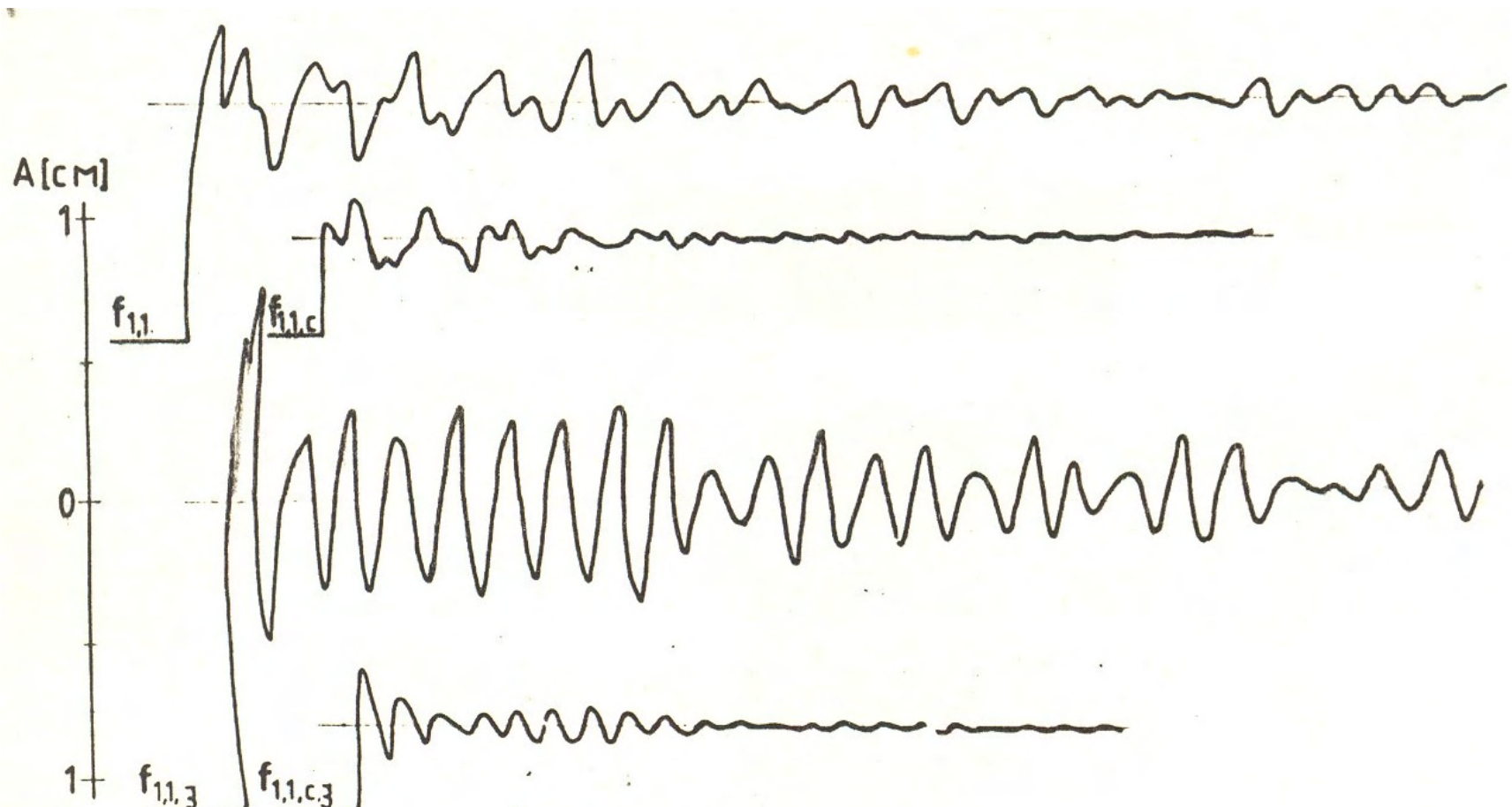




ALFA = 0.00 BETA = 0.00 W = 0.00

SCALE	TARTON LAULULAVAN KATOS	0JORG127
0.92151 CMD/M	TALLINNAN PTI --- PI-YHTIOT	FIG 5





25 Гц



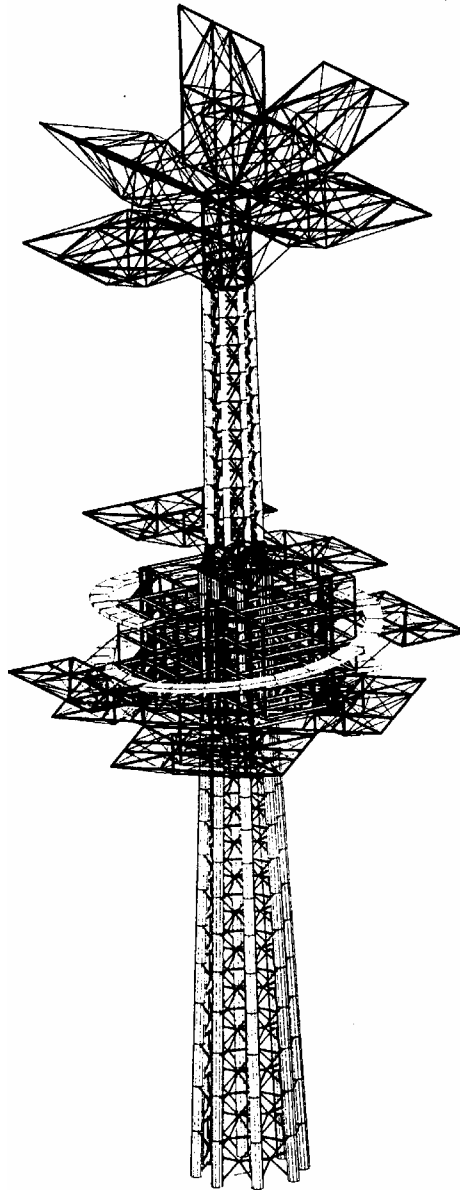








IX Puittornid ja mastid



The tower of the Earth,
projekteeritud Pariisi
milleeniumiks (2000.a.)

Kõrgus 200 m

8 puitposti.

Jäi ehitamata







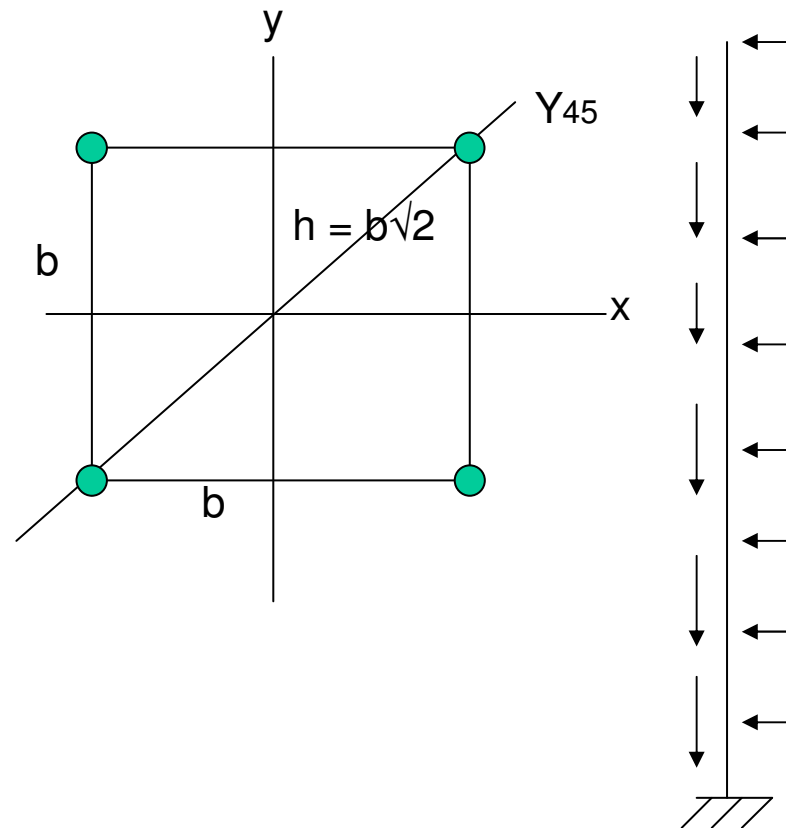








(Puit) tornide arvutamisesest



Arvutamisest

Torne arvutatakse kui sõrsetikkonsooli, mis kinnitatud alusesse (vundamenti). Vertikaalkoormus G jaotatakse ühtlaselt vööpostide vahel.

$$N = N_1 \pm N_2 ,$$

$N_1 = G/(n \cdot \cos \alpha)$ – sisejõud vööpostis ühtlaselt jagatud vertikaalkoormusest G

N_2 – sisejõud vöös horisontaalkoormustest, mis põhjustatud ümberlökkavast momendist

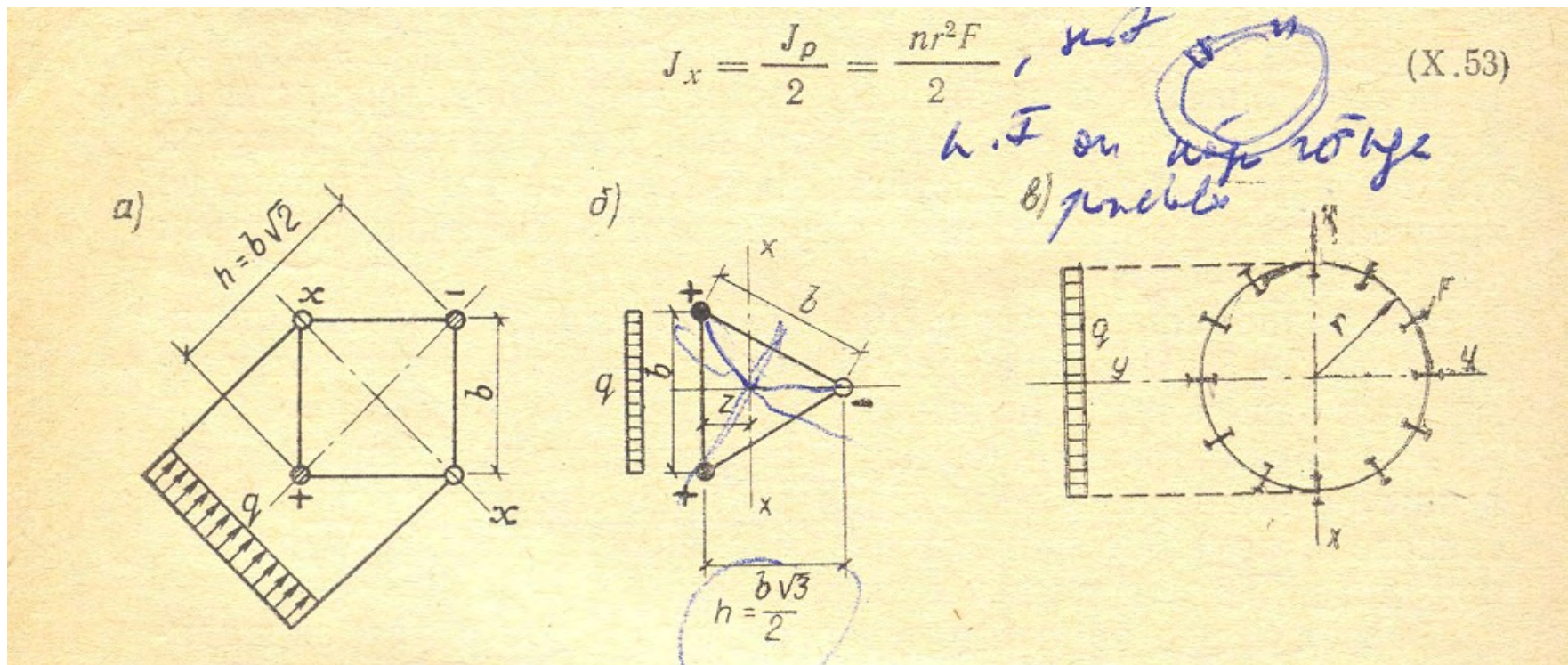
Neljatahulises tornis tekib tuulekoormusest vööpostis suurim jõud, kui tuulekoormus mõjub torni ühe diagonali suunas, kuna momenti võtab siis vastu ainult kaks vööposti:

$$N_2 = M/b\sqrt{2}$$

Arvutamisest

Kolmetahulise torni puhul tekib maksimaalne sisejõud vöö postis

$$N_2 = 2M/b\sqrt{3}$$



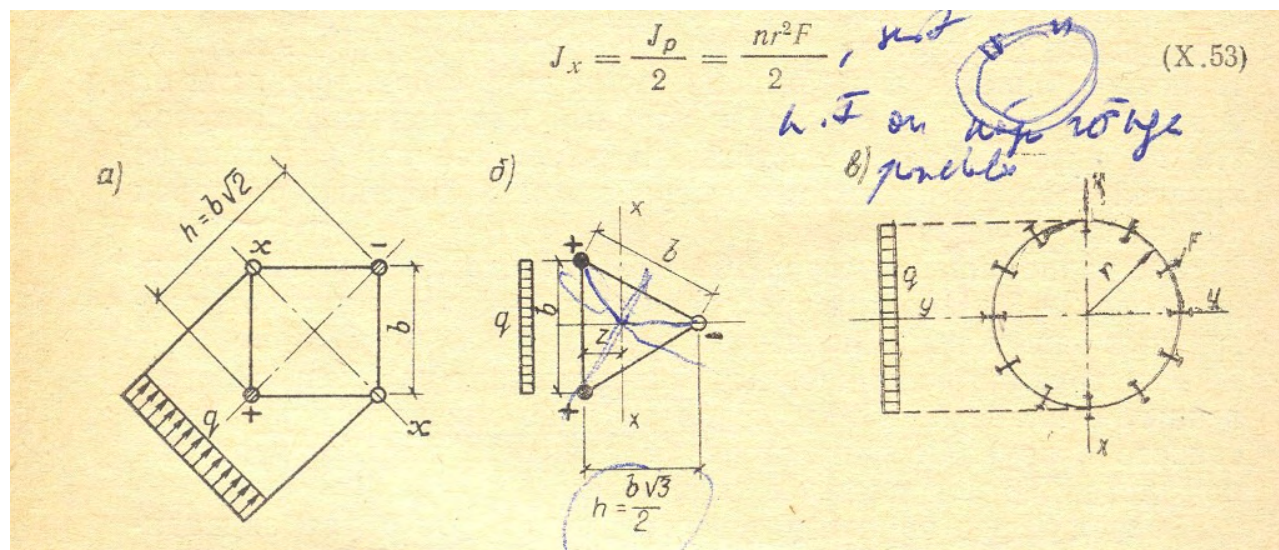
Arvutamisest

Ringikujulise põhiplaaniganitorni puhul, kus on palju poste igäüks ristlõikega A posti sisejõud momendist arvutatakse:

$$N_2 = A \cdot \sigma = M/W_x \cdot A = M \cdot r \cdot A/I_x = 2M/(n \cdot r)$$

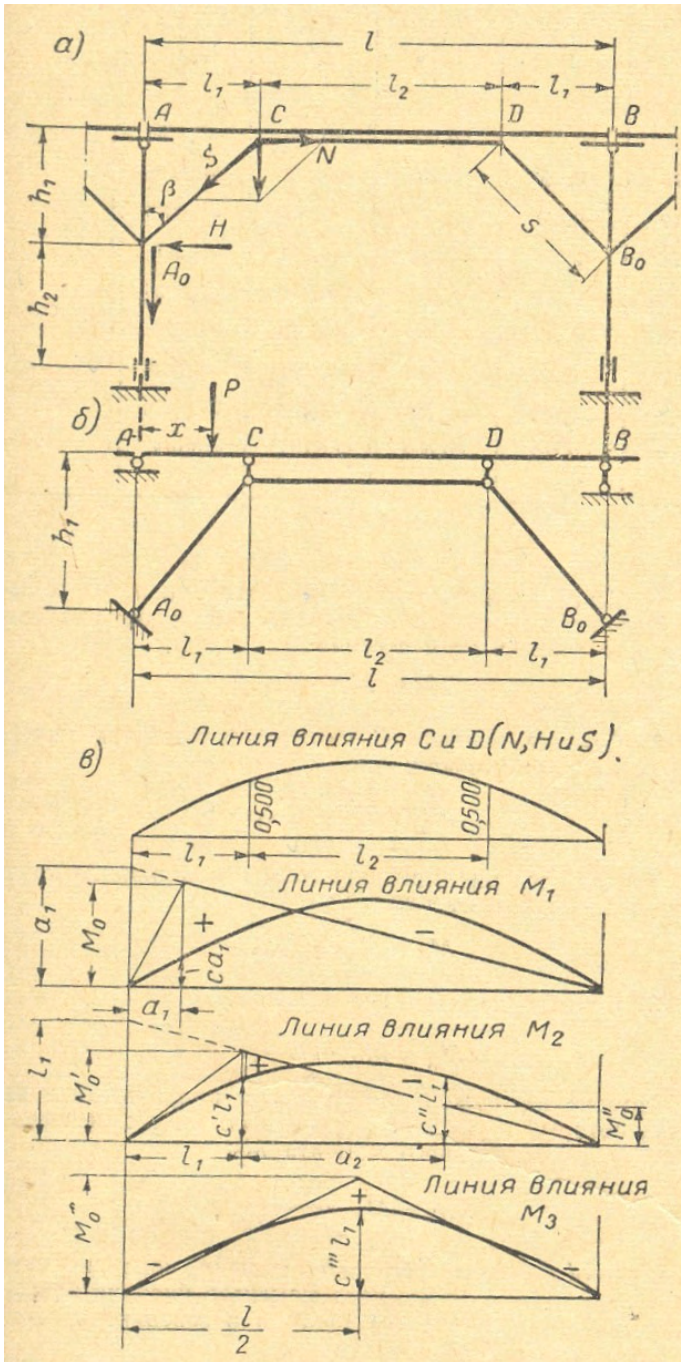
kus n on postide arv

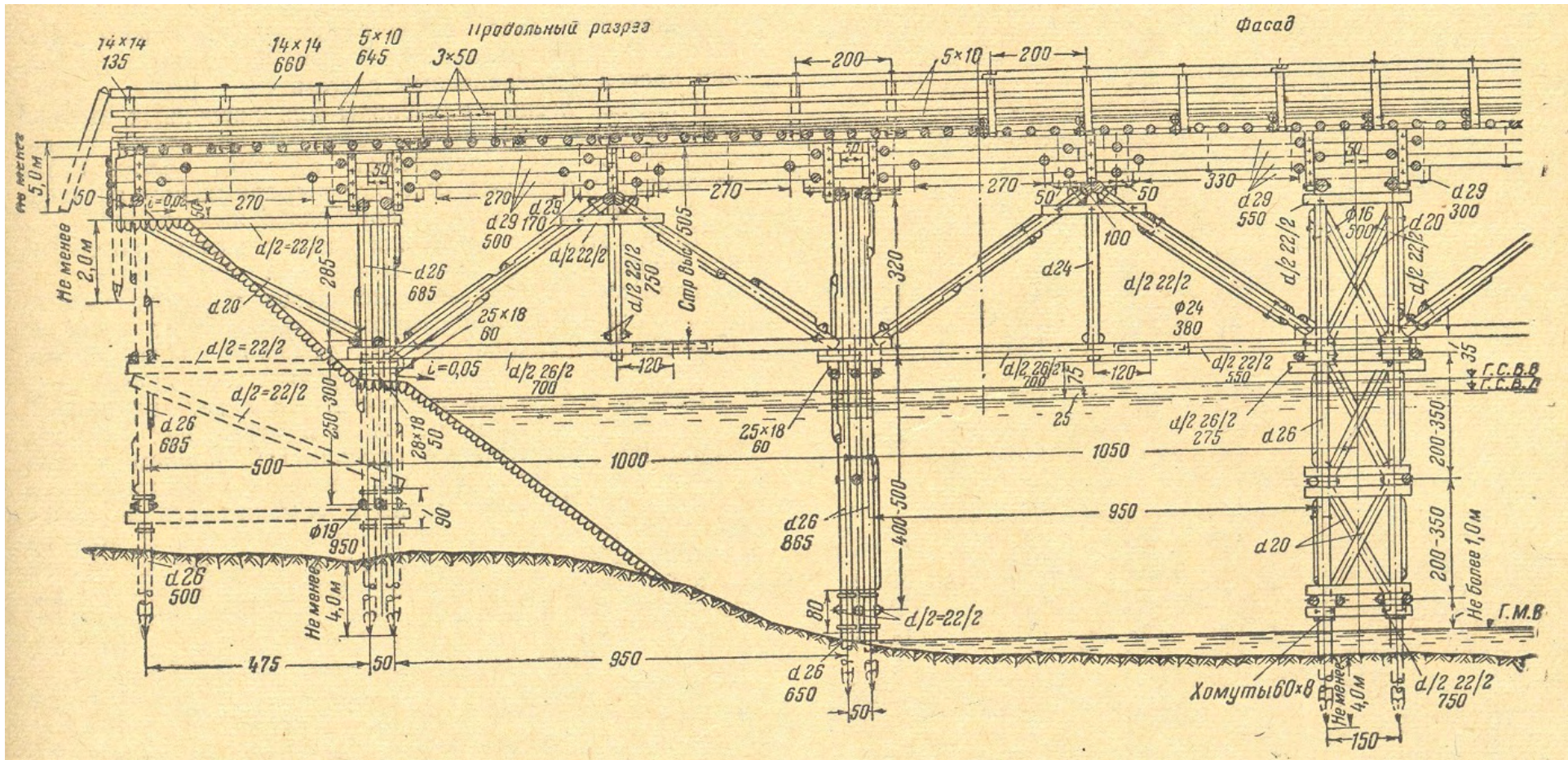
ja $I_x = I_p/2 = n \cdot r^2 \cdot A/2$

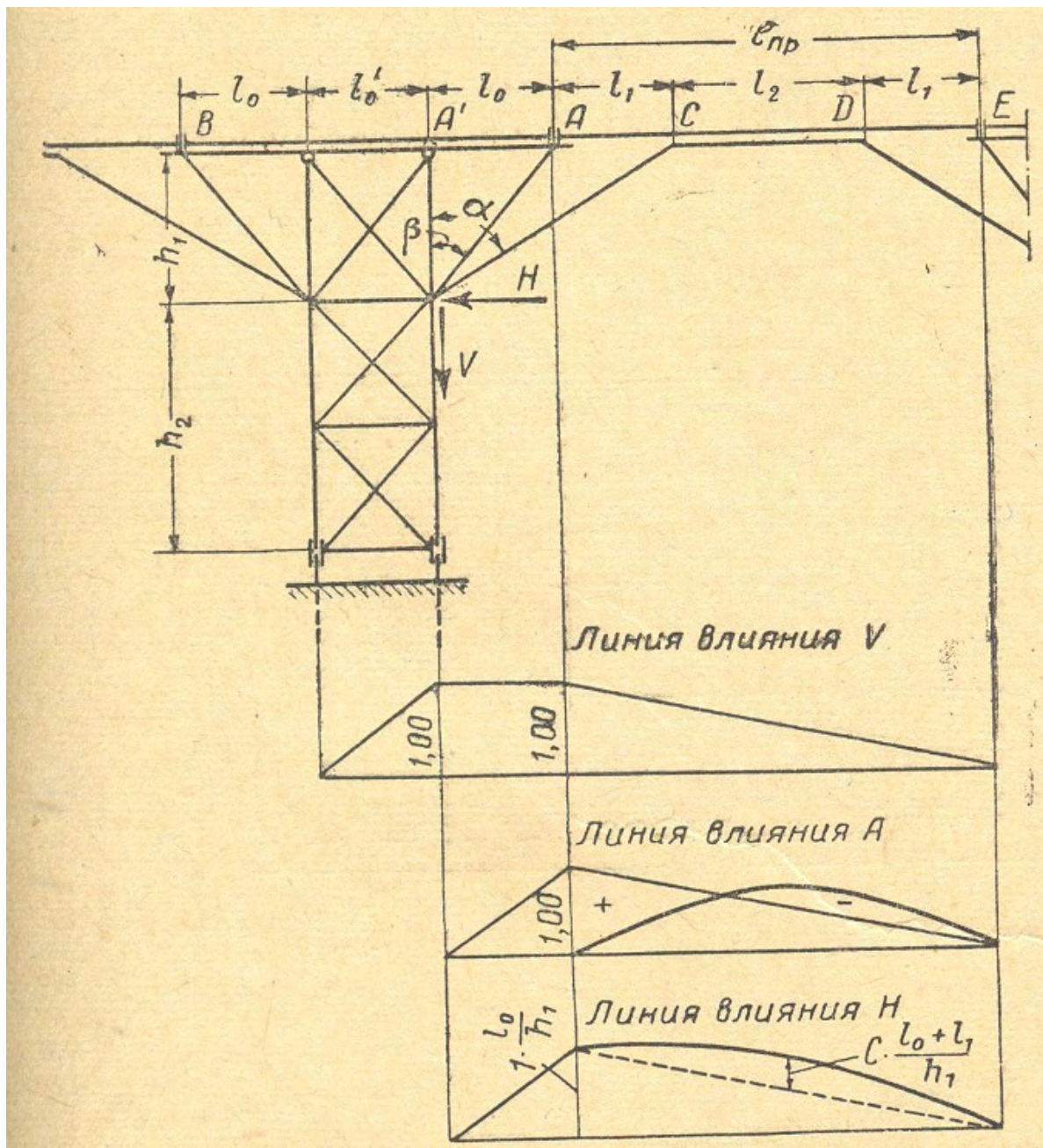


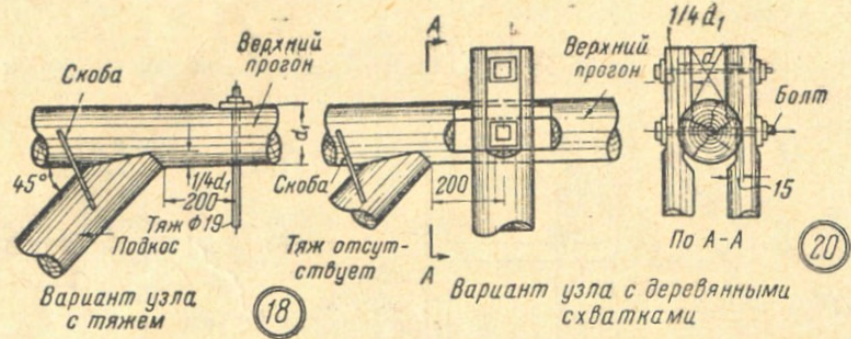
X Puitsillad, estakaadid, galeriid

- Konstrueerimine ja arvutus vastavalt sildade koormuste standardile, puitkonstruktsioonide projekteerimise standardile EVS 1995-1-1:2005 ja puitsildade standardile EVS 1995-2:2005;
Koormused osa 3: Sildade liikluskoormused EVS-EN 1991-2:2004

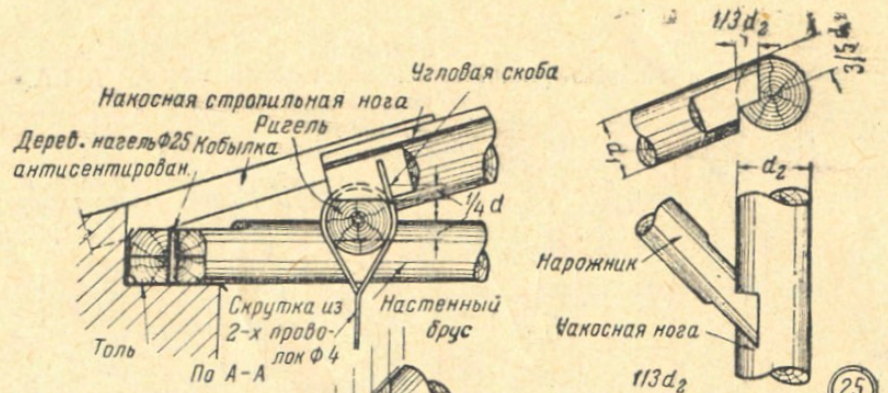




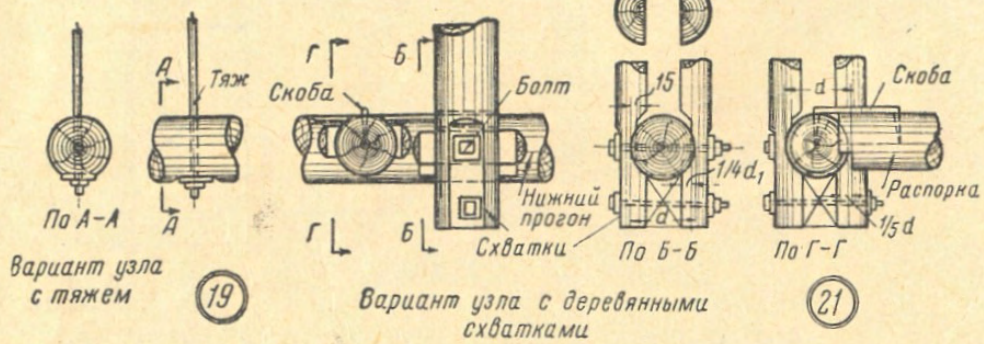




18



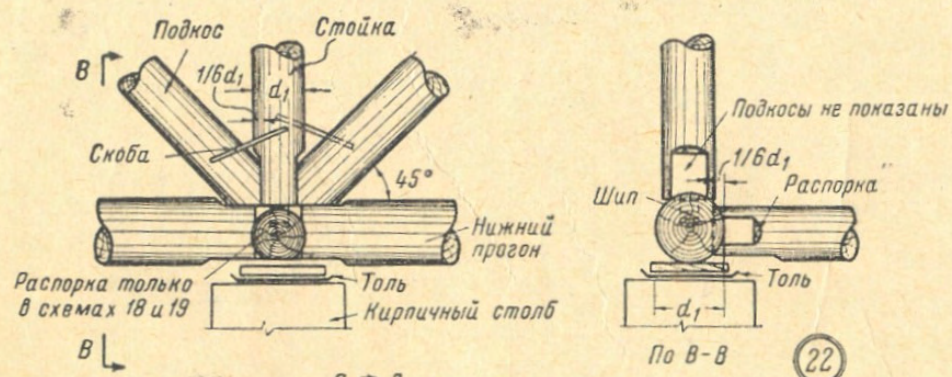
24



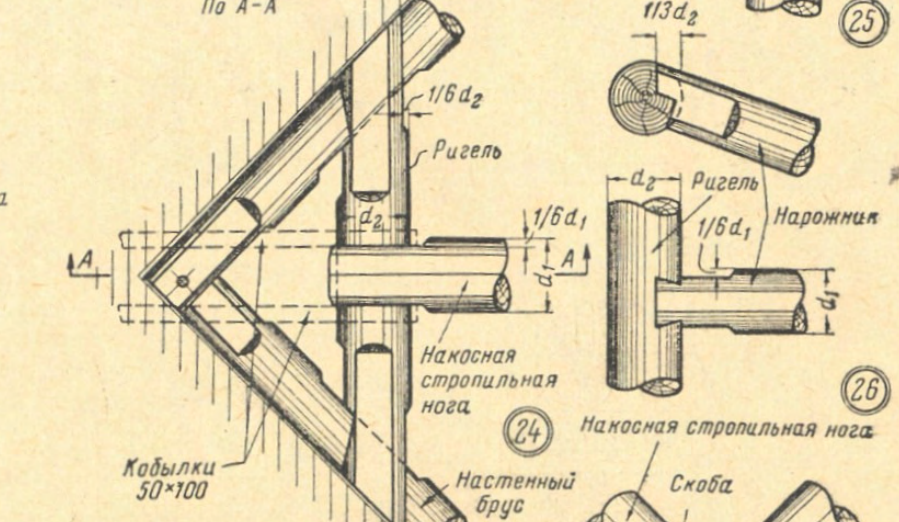
19

Вариант узла с деревянными схватками

21

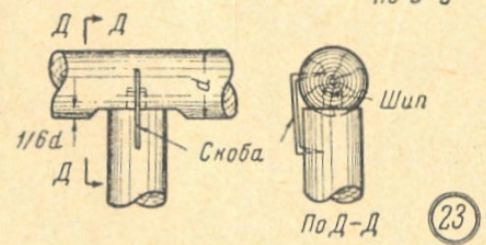


22

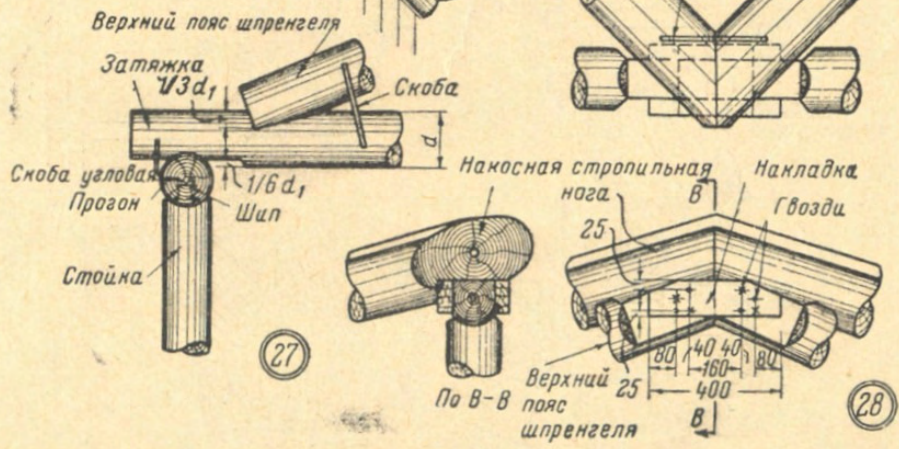


25

26

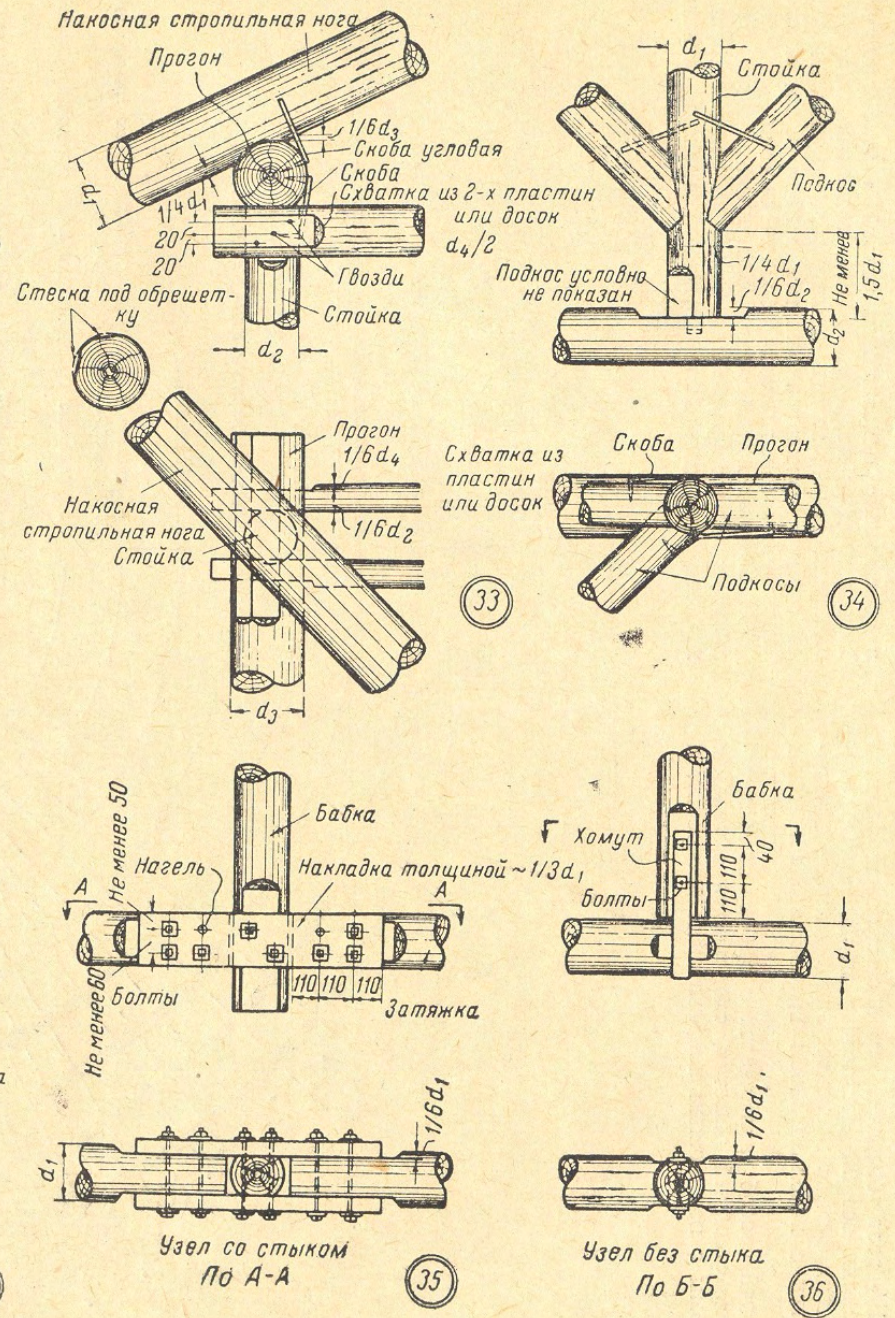
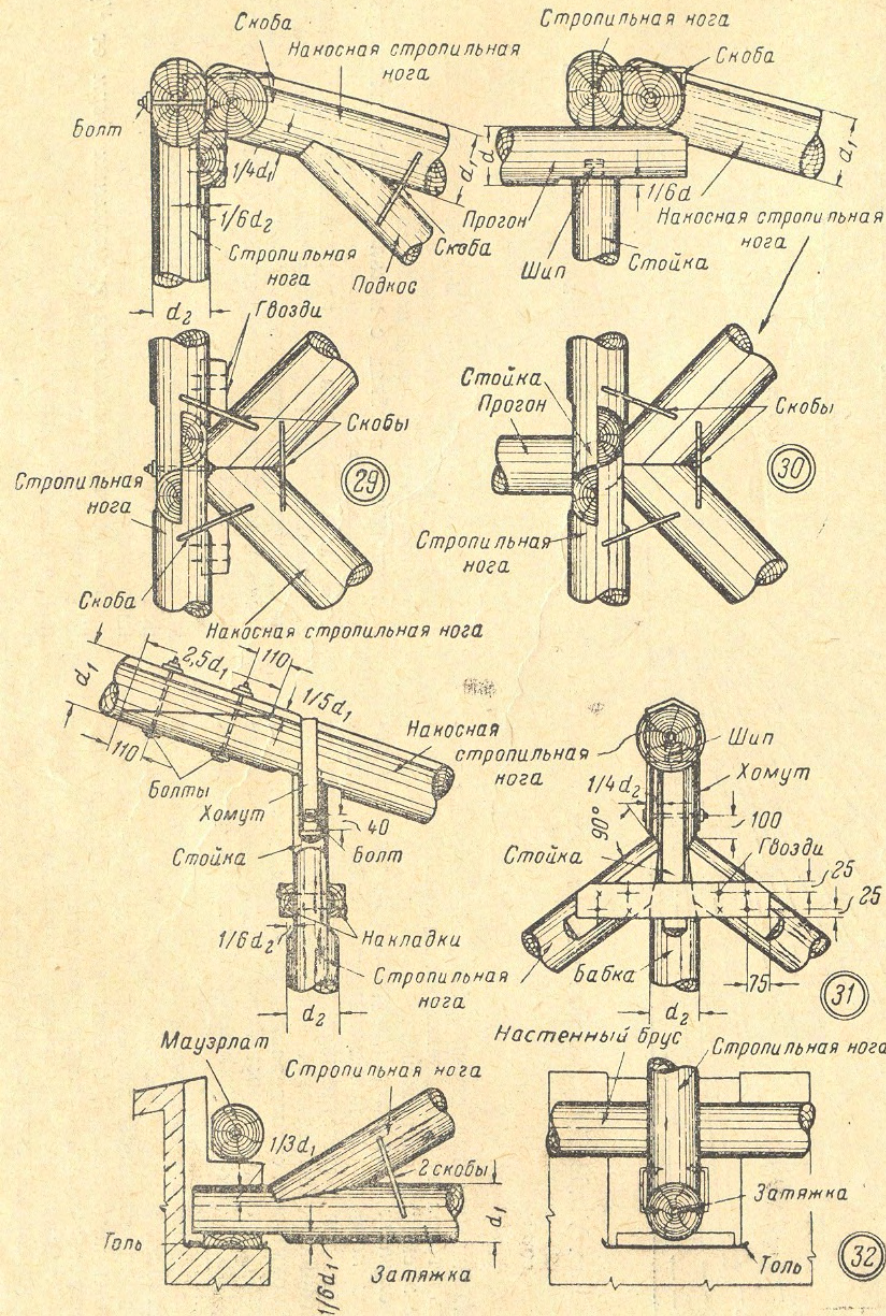


23



27

28



Tynset'i maantee-sild



- Kogupikkus 125 m
- Laius 10 m
- Maks. sildeava 70 m
- Ehitusaeg 2001
- Ehitusmaksumus 14.7 MNOK

- Kreosootimmutus
- Pingelamellplaat

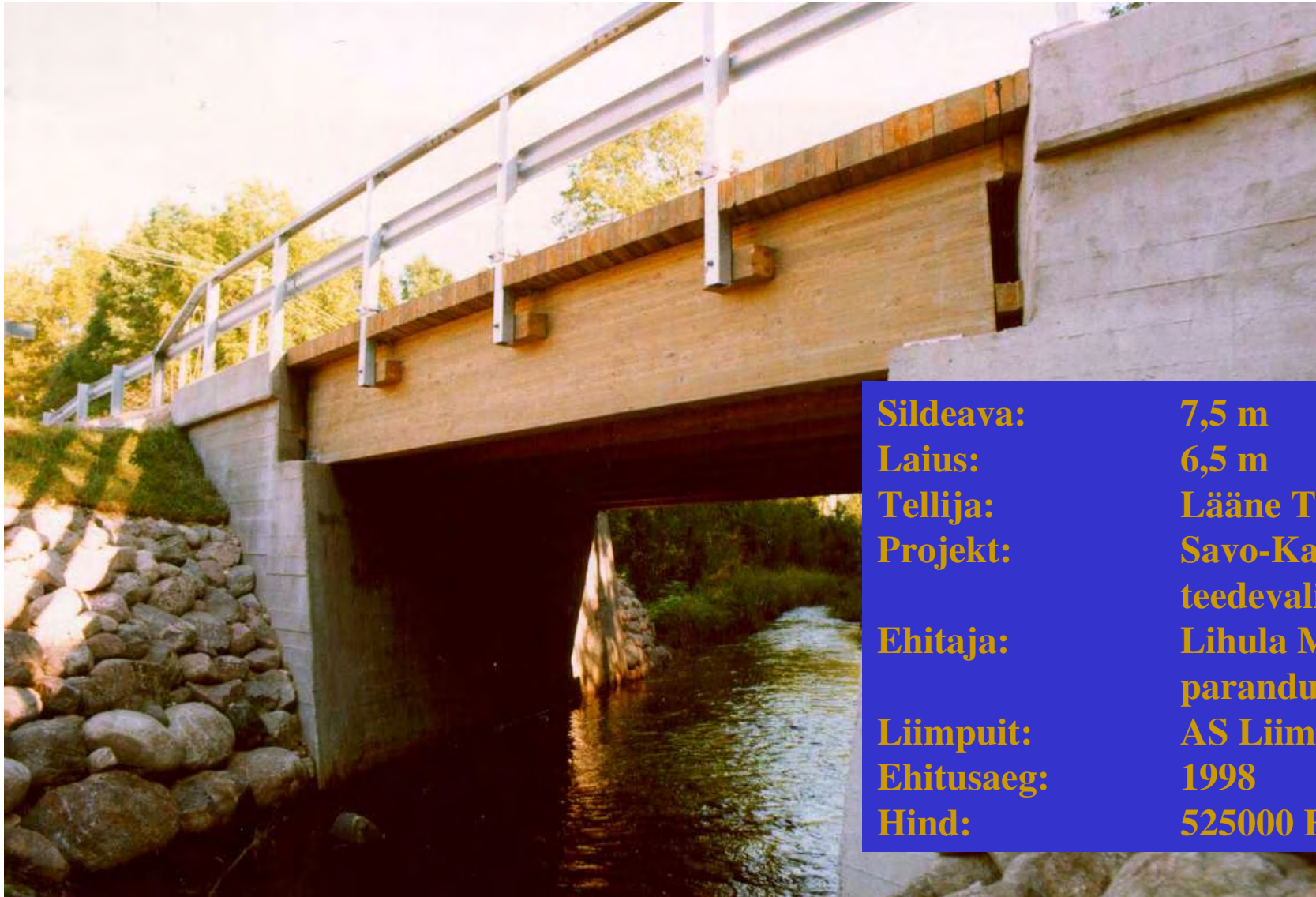








Tagavere sild



Sildeava:	7,5 m
Laius:	6,5 m
Tellija:	Lääne TV
Projekt:	Savo-Karjala teedevalitsus
Ehitaja:	Lihula Maa- parandus
Liimpuit:	AS Liimpuit
Ehitusaeg:	1998
Hind:	525000 EEK

Merirahu jalgteesild

Pikkus: 35,6 m
Sildeava: 24 m
Laius: 3 – 5,5 m



Tellija: AS Hestlinger

Projekteerija: AS Resand

Ehitaja: AS Via Pont

Liimpuit: AS Liimpuit

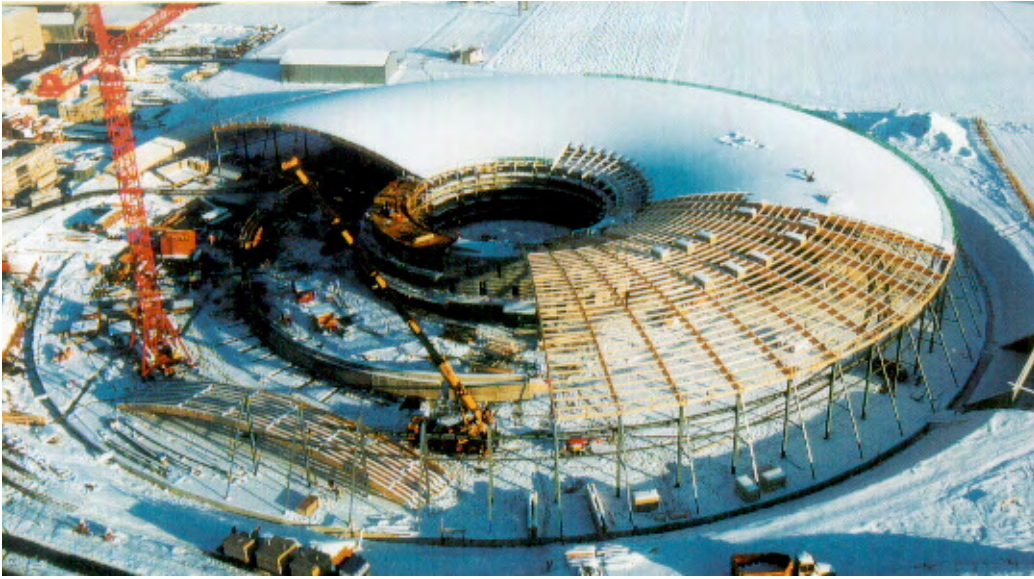
Koormus: 4,4 kN/m²; 80 + 40 kN

Ehitatud: 2000

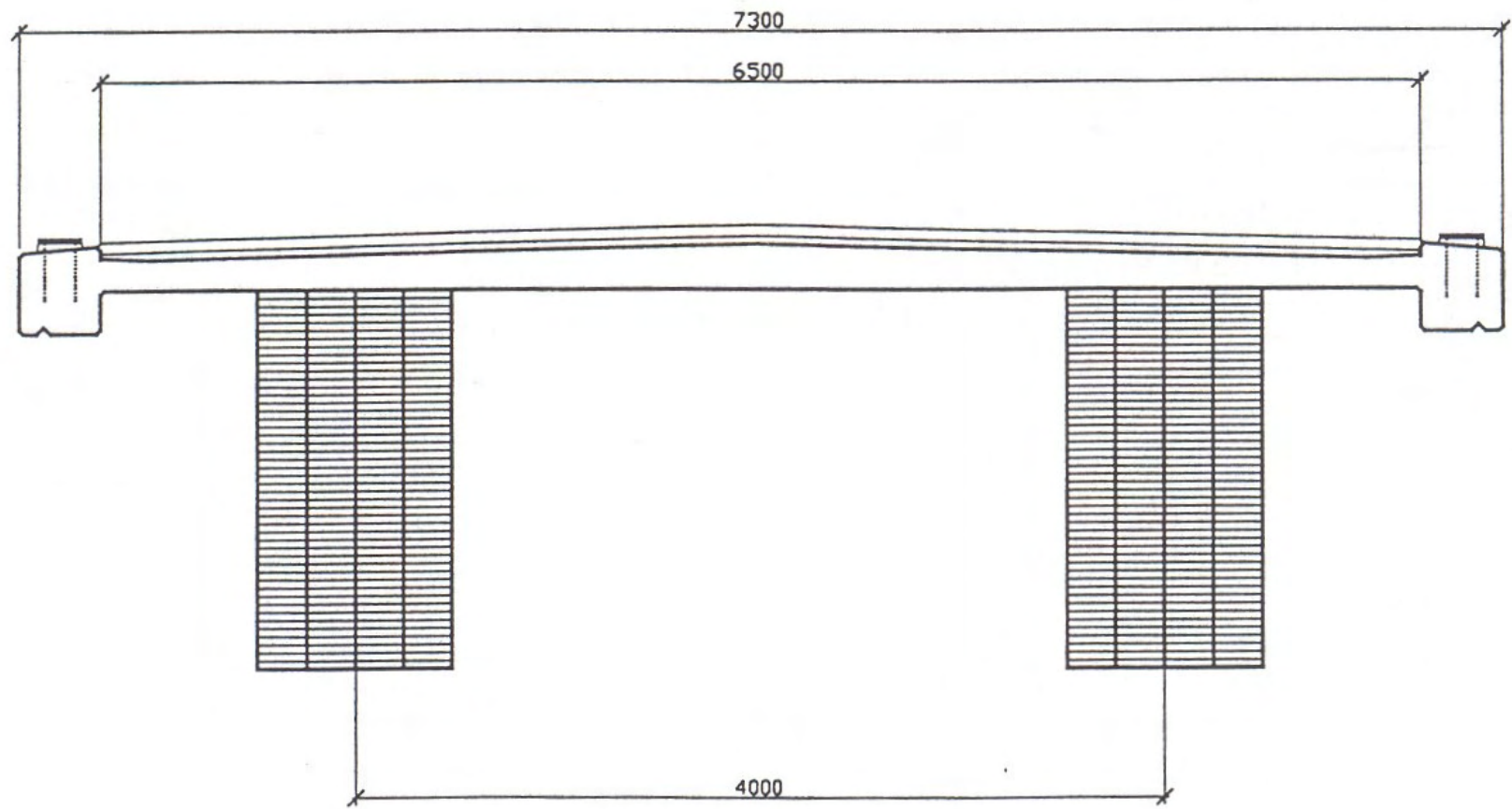
Hind: 4,3 milj EEK

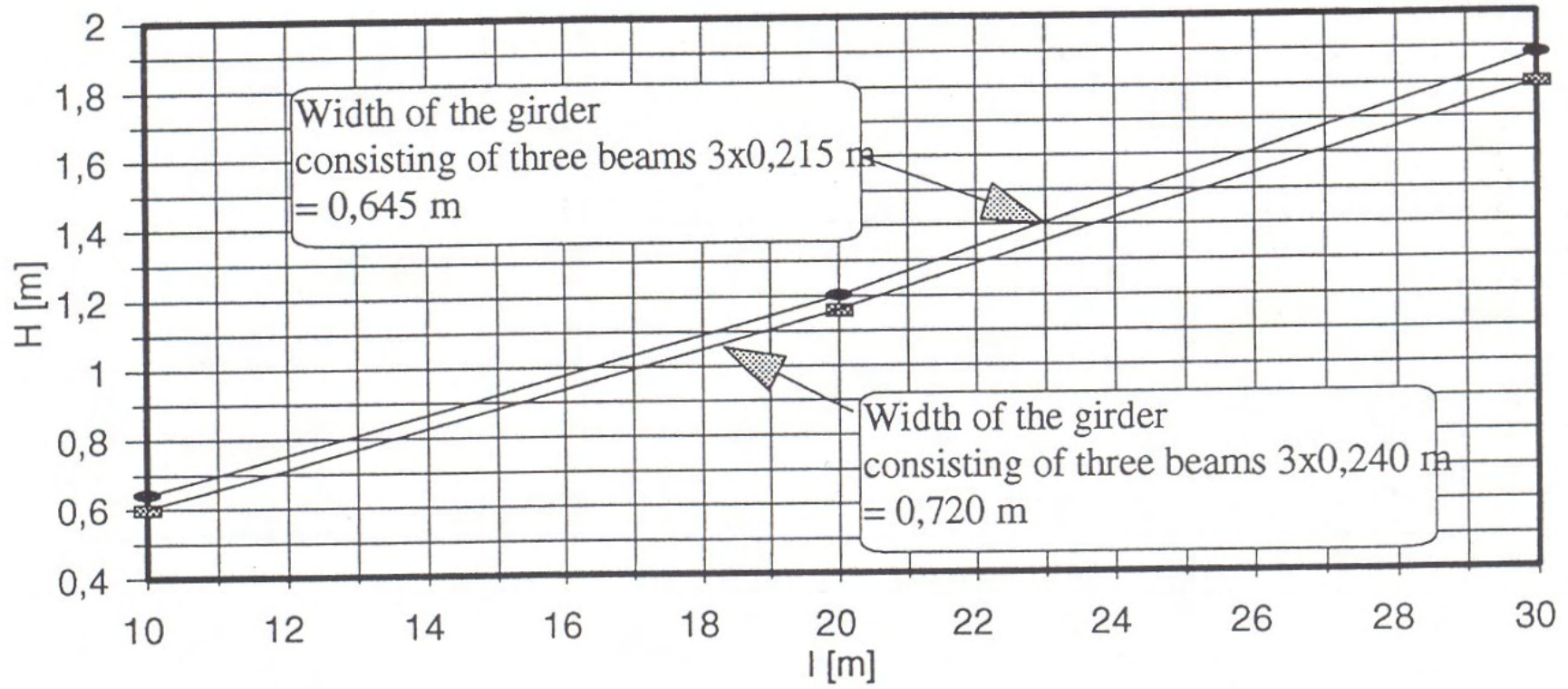


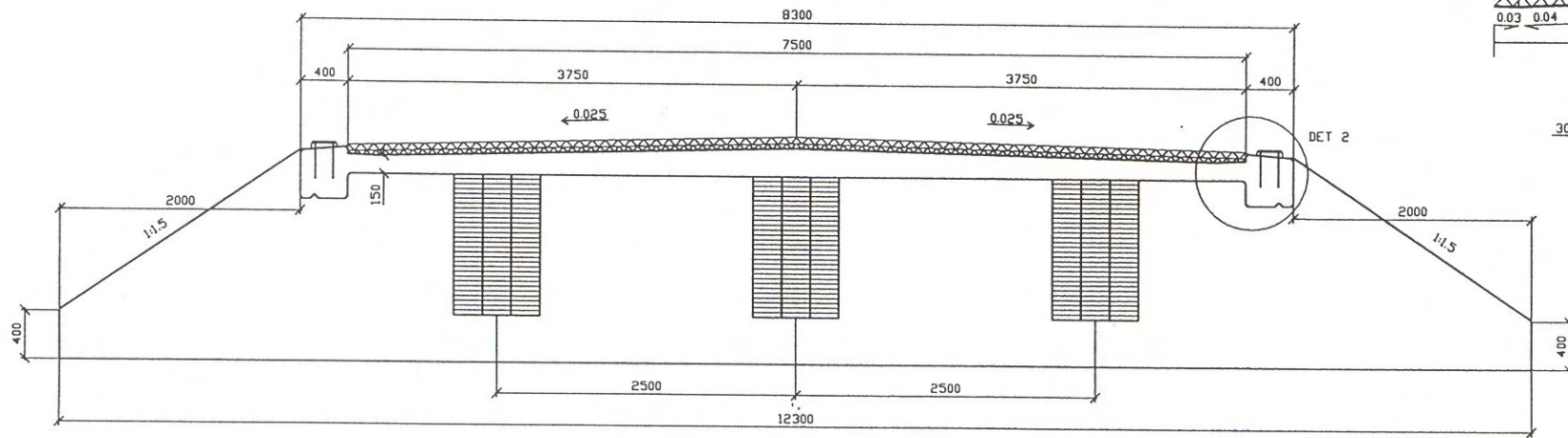
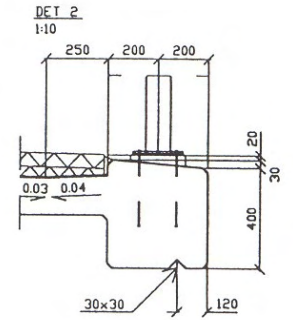
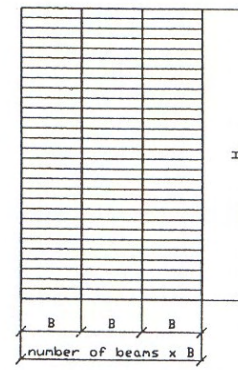
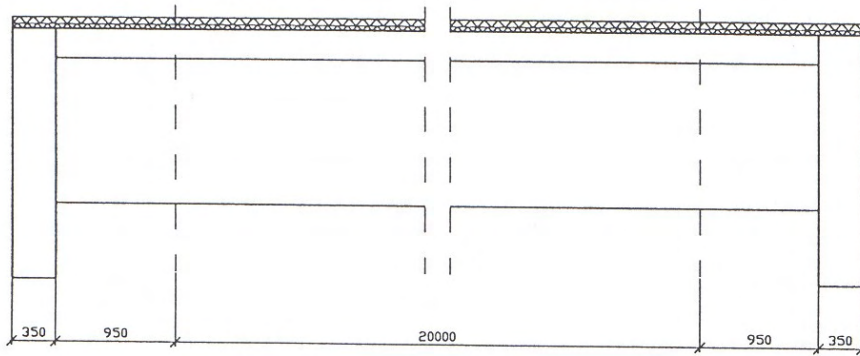


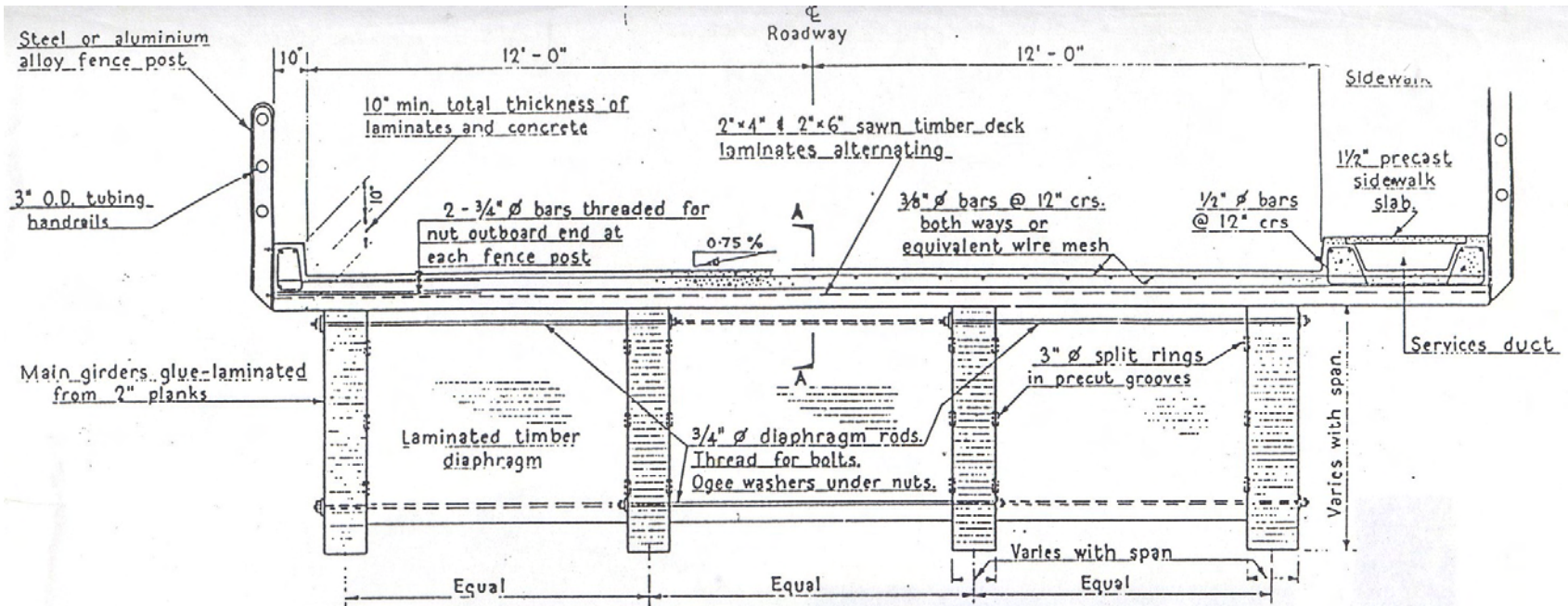




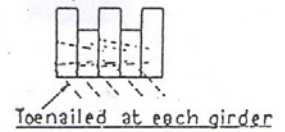
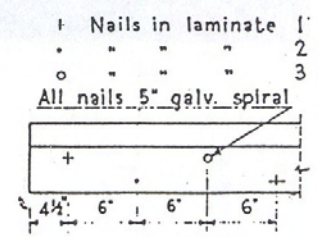
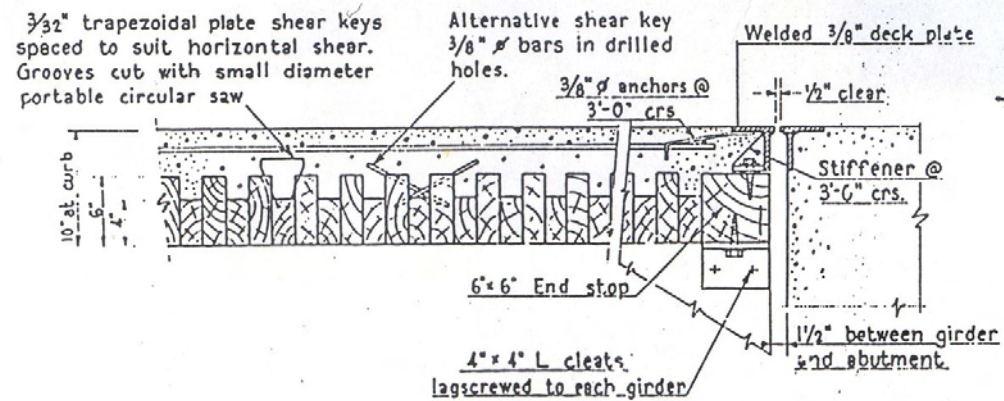




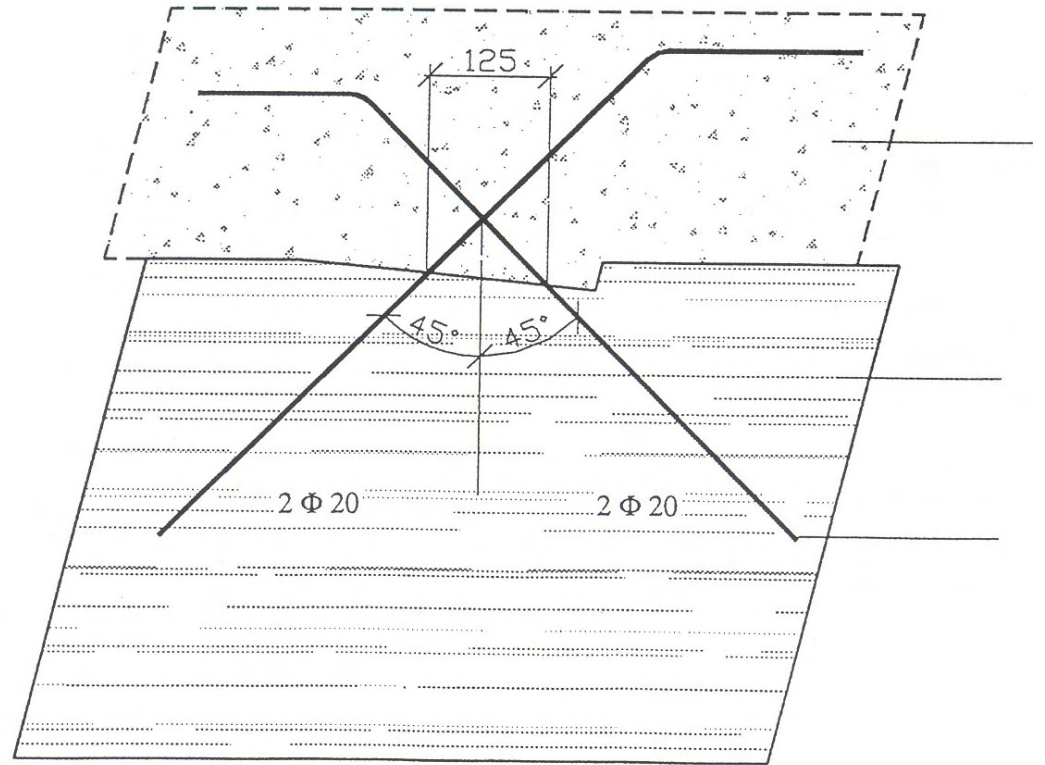
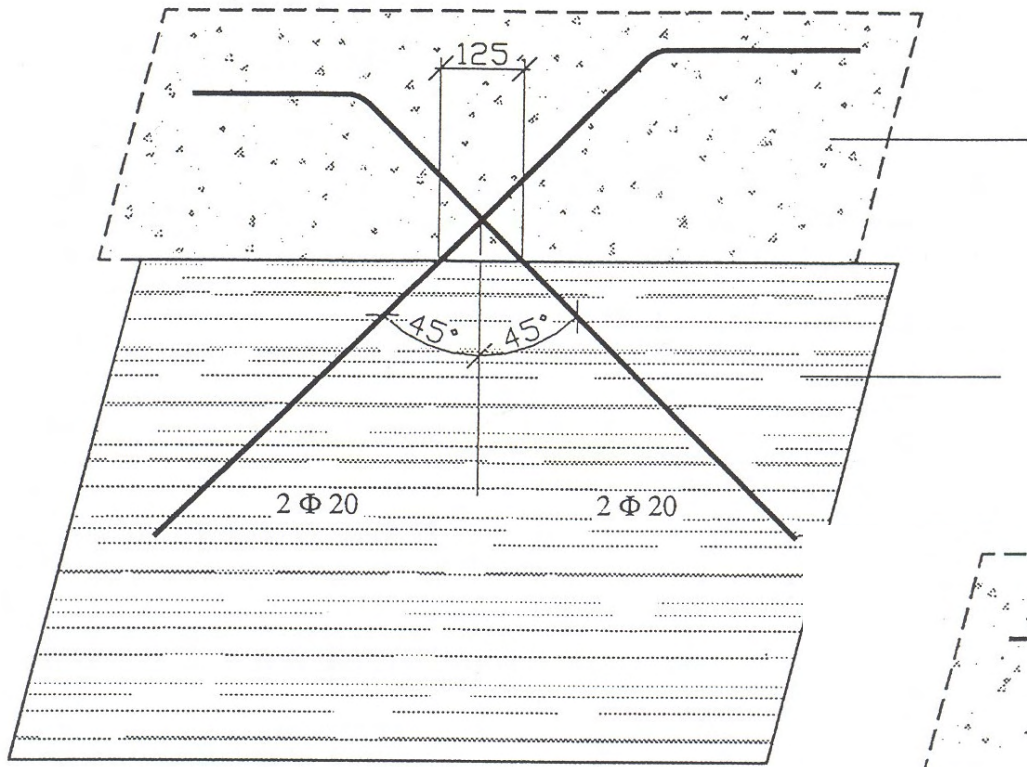


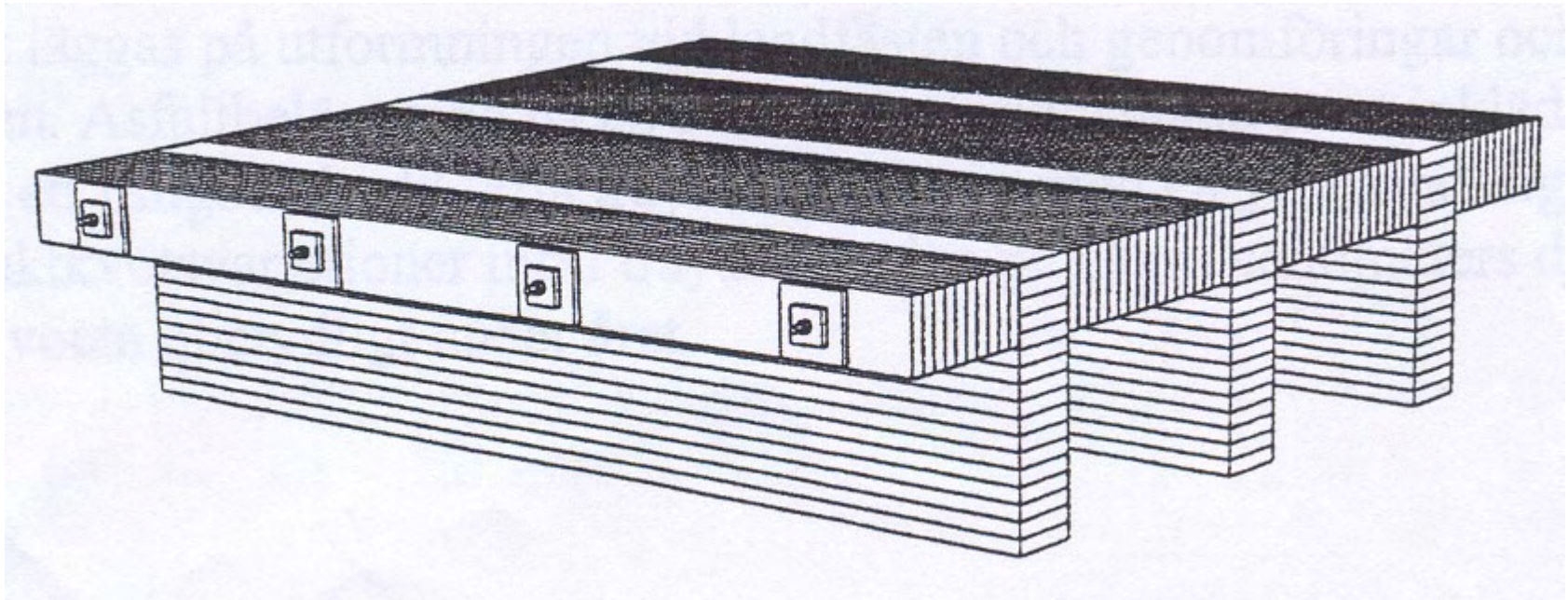
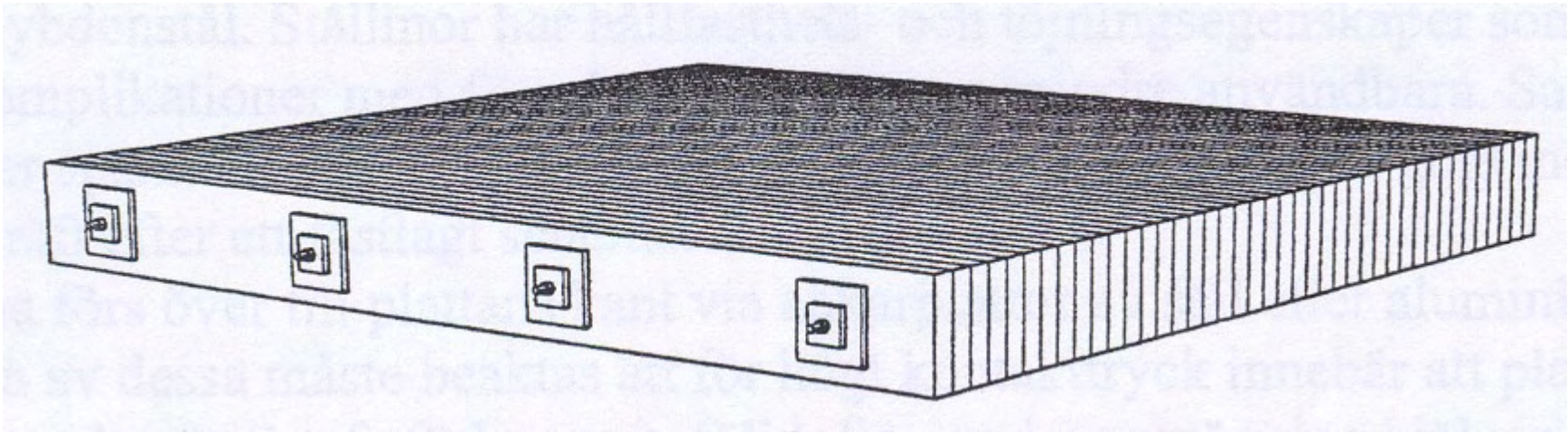


Cross-Section



Nailing Pattern





XI Suureavaliste (mõõtmeliste) raudbetoonkonstruktsioonide puit- ja puitmetall raketised

Raketisi kasutatakse betoon- ja raudbetoonkonstruktsioonide (vundamendid, karkassid, vahelaeplaadid, kaar-, völv-, kuppel-, koorikkonstruktsioonide valmistamisel ehitusplatsil, vahel ka kivivölvide ladumisel.

Valmistamisel kasutatakse puitu, puidupõhjalistest materjalidest plaatmaterjale, plastikuid, terasest- või mõnest muust metallist materjale.

Raketised koosnevad:

- põrandast, mis on betooni paigaldamise vorm
- põrandat toetavatest taladest või kaartest
- vajaduse korral talasid või kaari toetavatest postidest.

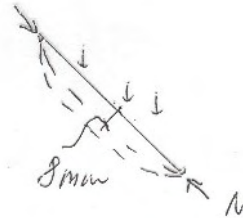
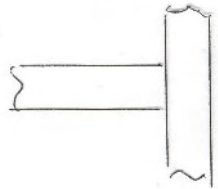
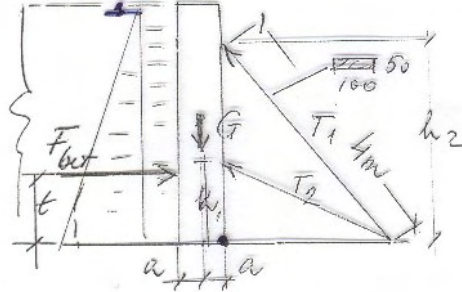
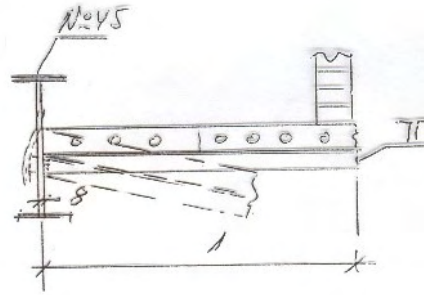
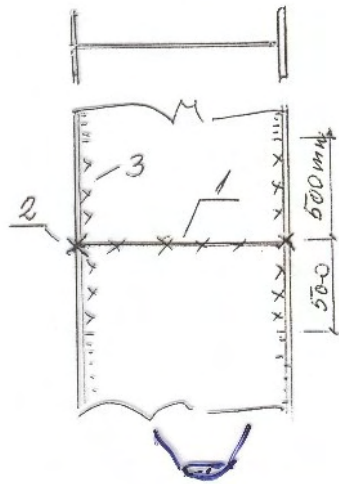
.....

Arvutuse iseärasusi:

- alaline koormus, omakaal, jne
- ajutine koormus, mis on paigaldatud kõige ebasoodsamas asendis, mis koosneb püstitatava ehituskonstruksiooni massist, seadmete massist, muude materjalide massist, tuulekoormus, värske betooni hüdrostaatiline surve, arvestades koormuse dünaamilisust (koormus betooni vibreerimisest, löök betooni paigaldamisel, jne., sh arvutus ümberlükkele - püsivusele

..... raudbetoonkonstruktsioonide puit- ja puitmetall raketised

- ✓ Betoon, raudbetoonkonstruktsioonide raketiste projekteerimine ja nende eriti nende koormuste arvutamine toimub erinormide alusel.
 - 1) Eriline küsimus on raketistele mõjuvate koormuste määramine. Praegu tuleks lähtuda lähiajal ilmuvast
EVS-EN 1991-1-6:2006, so Eurokoodeks 1: Ehituskonstruktsioonide koormused. Osa 1-6: Üldkoormused, Ehitusaegsed koormused.
EVS-EN 1991 -1-1.
Konstruktsioonide arvutamisel tuleb lähtuda vastavatest puit või teraskonstruktsioonide arvutamise vastavatest EVS-idest.
 - 2) Kui on tegemist mingi firma poolt valmistatud monteeritavate raketistega, siis tuleb kasutada selle firma raketise kasutamise juhenditest, kus on samuti antud arvestatavate koormuste suurused ja muud eeskirjad (näiteks Ramirendi poolt kasutatavad Hünnebeck-i seinaraketiste süsteem Manto, vahelae süsteem Variomaks või, teine tootja PERI raketise tüübid, arvutus käib küll DIN normide kohaselt)



$$F_{bet}^{aw} = F_{bet}^{norm} \cdot 1,3$$

$$G^{aw} = G^{norm} \cdot 0,8$$

$$F_{bet}^{aw} \cdot t - G^{aw} \cdot a = \Delta F$$

$$\Delta F = T_1 \cdot h_1 + T_2 \cdot h_2 \quad ?$$

$$\lambda = \frac{l_{aw} = 4m}{l_{min} = 2,44} \approx 280, [\lambda] \leq 150$$

$$M = N \cdot e$$

$$M = N(e + f)$$

$$\sigma = \frac{N}{A_{red}} + \frac{M}{\xi \cdot W_n} \leq R$$

$$\xi = 1 - \frac{\lambda^2 \cdot N}{3100 \cdot R \cdot A} \approx 0$$

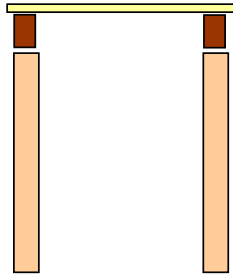
(A)

$$\xi = 1 - \frac{N}{\varphi \cdot R_c \cdot A}$$

2

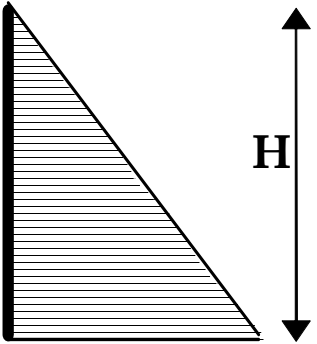
RAKETISE ARVUTUS

Vertikaalkoormused

Raketise omakaal	Vastavalt tööjoonistele
Värske betooni omakaal	$\approx 2500 \text{ kg/m}^3$
Sarruse omakaal	$\approx 100 \text{ kg/betooni } 1 \text{ m}^3 \text{ kohta}$
Koormus inimestest ja transpordist	 <ul style="list-style-type: none"> ■ laudisele $\approx 2,5 \text{ kN/m}^2$ ■ partele $\approx 1,5 \text{ kN/m}^2$ ■ tugedele $\approx 1,0 \text{ kN/m}^2$
Koormus vibreerimisest horisontaalpinnale	$\approx 1,0 \text{ kN/m}^2$

RAKETISE ARVUTUS – 2

Horisontaalkoormused

Tuulekoormus	
Koormus vibreerimisest	$\approx 4 \text{ kN/m}^2$
Koormus betoonisegu väljalaadimisest: -Renn, torustik, lont -Kopp mahuga $\leq 0,8\text{m}^3$ ($>0,8\text{m}^3$)	$\approx 4 \text{ kN/m}^2$ $\approx 4 \text{ kN/m}^2(6\text{kN/m}^2)$
Värske betoonisegu külgsurve – P Valemi kasutuspiirkond tihendamisel: • Sisevibraatoriga $H \leq R ; v < 0,5 \text{ m/s}$ • Välisvibraatoriga $H \leq R_1 ; v < 4,5 \text{ m/s}$	$P = \gamma H$ 
R – sisevibraatori tegevusraadius ($R \approx 0,75\text{m}$) R_1 – välisvibraatori tegevusraadius ($R_1=1,0\text{m}$) v – raketise täitmise kiirus betooniga, m/s	

RAKETISE ARVUTUS – 3:

Horisontaalkoormused

Juhul kui tingimused ei ole täidetud, siis:

$$P = \gamma(0,27v + 0,78)k_1k_2$$

k_1 Plastilisust arvestav tegur

Koonuse vajumine 0 ... 2 cm $k_1 = 0,8$

Koonuse vajumine 4 ... 6 cm $k_1 = 1,0$

Koonuse vajumine 8 ... 12 cm $k_1 = 1,2$



k_2 Välisõhu temperatuuri arvestav tegur

$t^0 = 5 \dots 7 \text{ °C}$ $k_2 = 1,15$

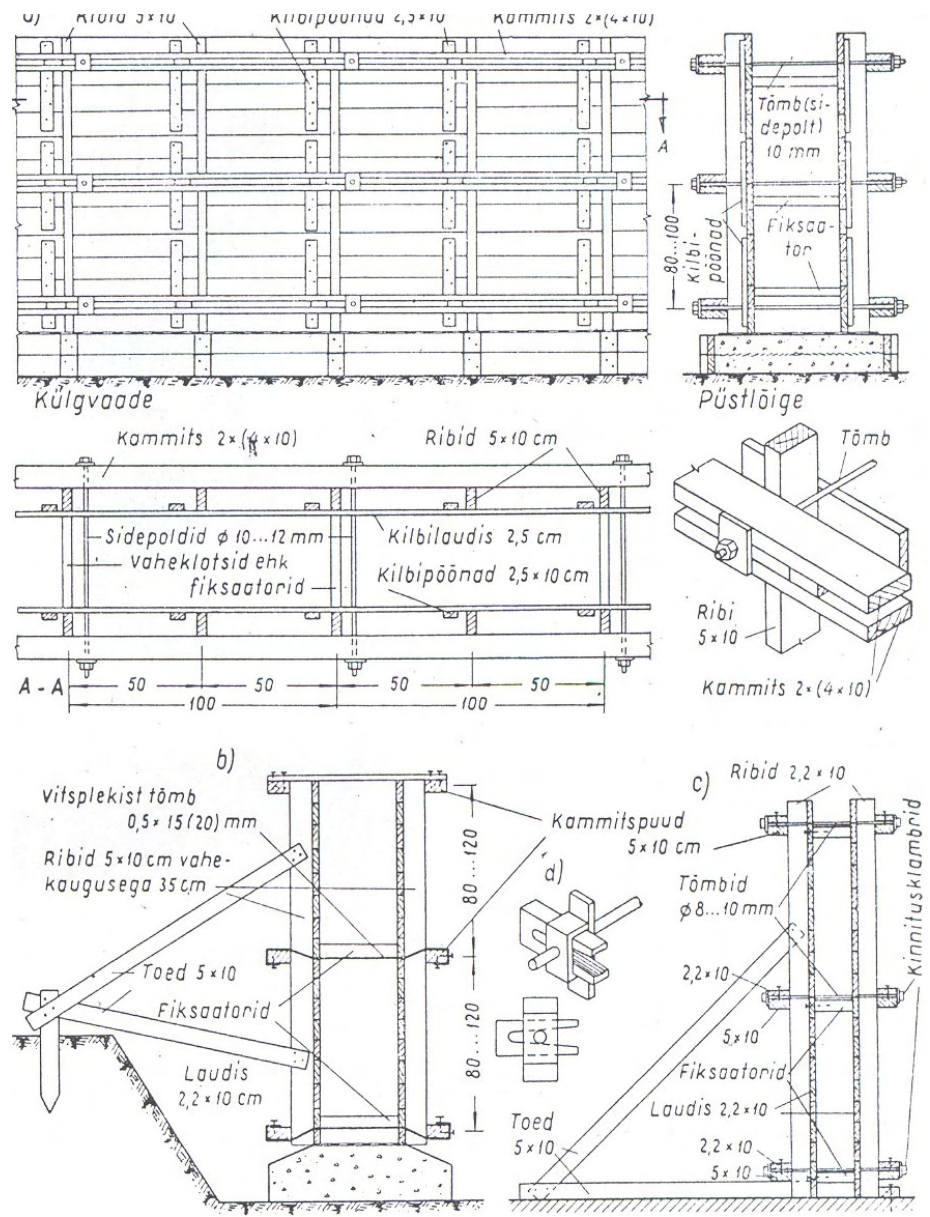
$t^0 = 12 \dots 17 \text{ °C}$ $k_2 = 1,00$

$t^0 = 28 \dots 32 \text{ °C}$ $k_2 = 0,85$

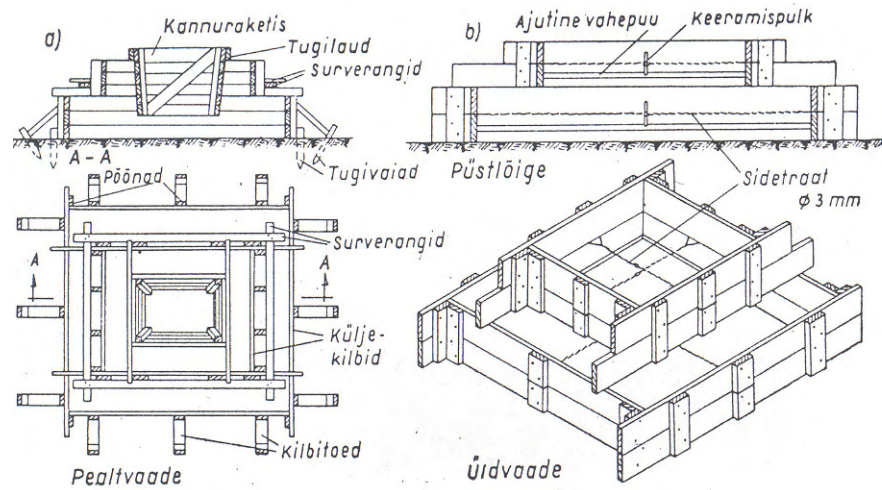


... raudbetoonkonstruktsioonide puit- ja puitmetall raketised

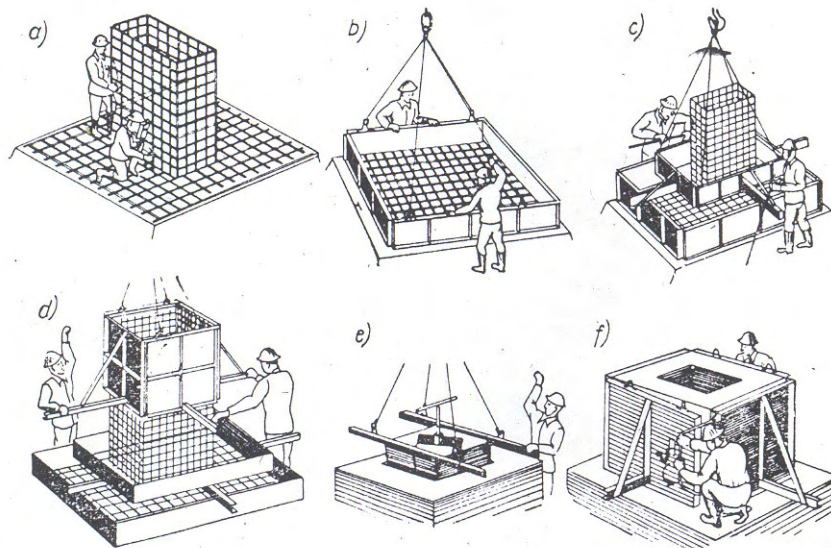
Alljärgnevalt mõningaid raketiste näiteid:



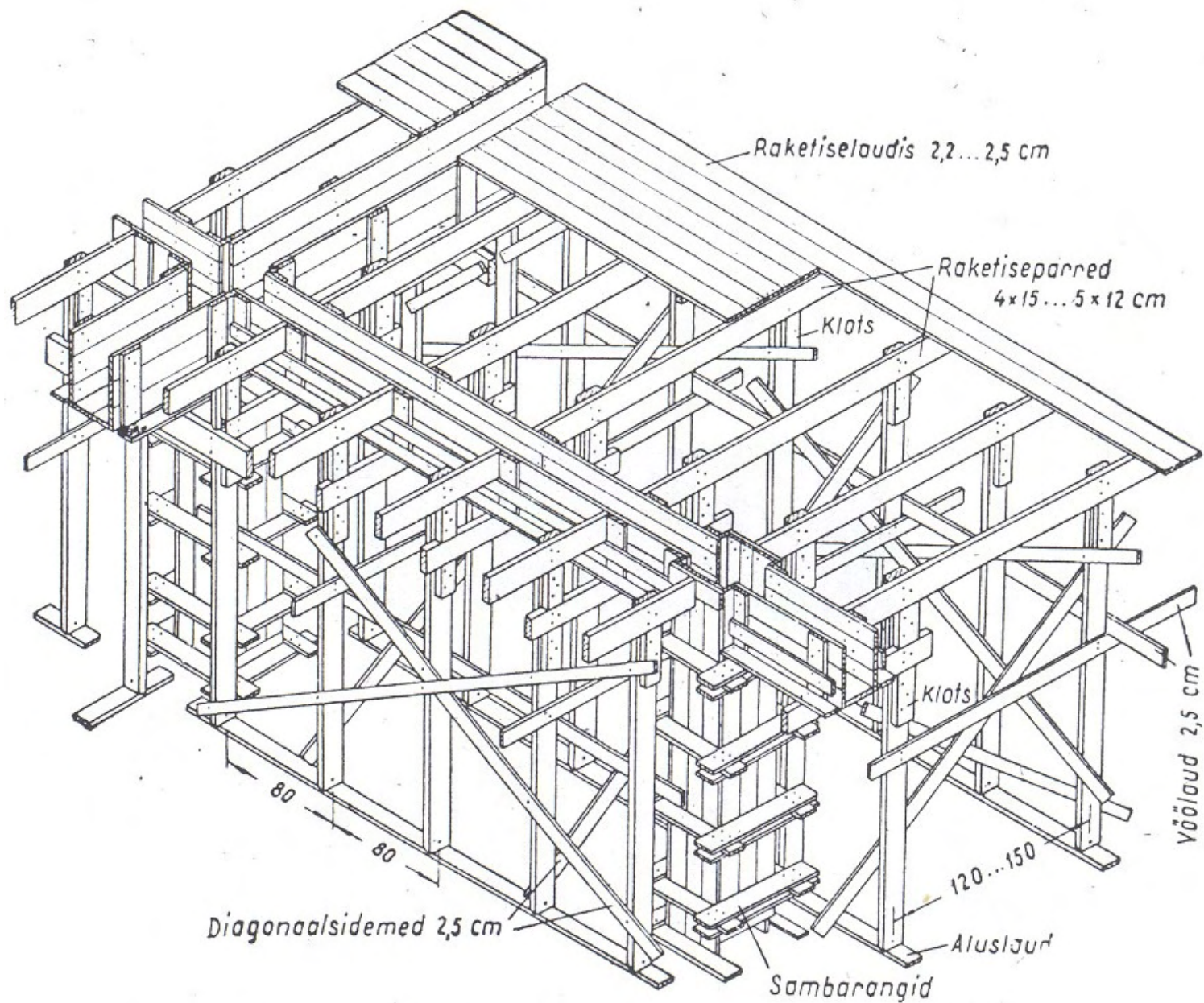
Joon. 195. Keldriseinte ja seinte raketised:
 a — kammitispuude ja sidepoltidega (põltõmbidega) keldriseinaraketis, b — vitsplekist tõmbidega keldriseinaraketis, c — ümarrauast tõmbide ja kinnitusklambritega seinaraketis, d — tõmbi kinnitusklamber



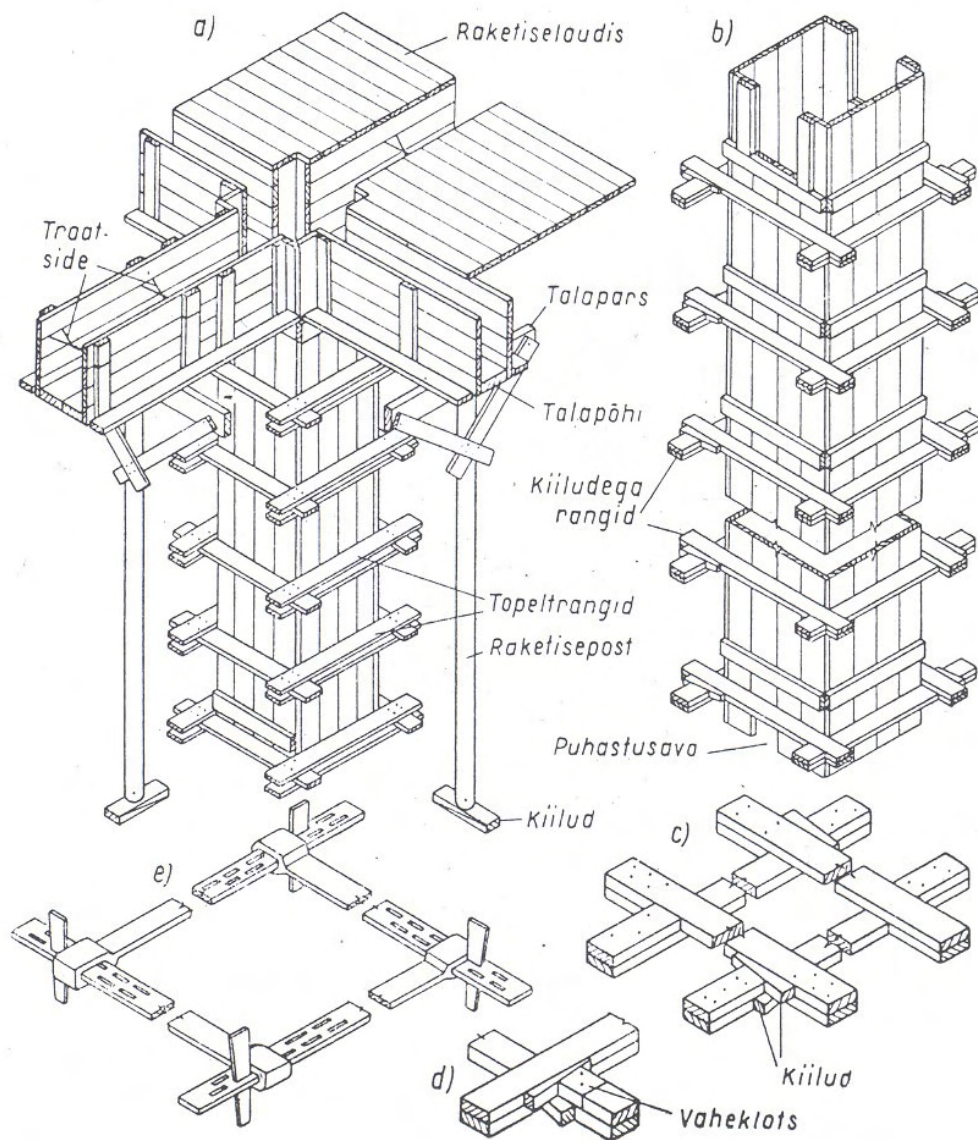
Joon. 197. Astmelise vundamendi raketis:
 a — kannvundamendi raketis, b — sambaaluse raketis



Joon. 198. Kannvundamendi metallraketis:
 a — armatuurikarkassi paigaldamine, b — alumise astme raketiseploki paigaldamine, c — teise astme raketiseploki paigaldamine, d — sambaaluse raketiseploki paigaldamine, e — kannu raketise kõrvaldamine pärast betoonimist, f — lahtiraketamine kanõlukkude vabastamise teel



Joon. 203. Raubbetoonkarkassiga hoone mitteinventaarne raketis



Joon. 205. Sambaraketis:
 a — mitteinventaarne sambaraketis koos talade raketisega, b —
 kiiludega inventaarsete rangidega sambaraketis, c — kiiludega rangid,
 d — vaheklotsiga rangi detail, e — reguleeritavad metallrangid





















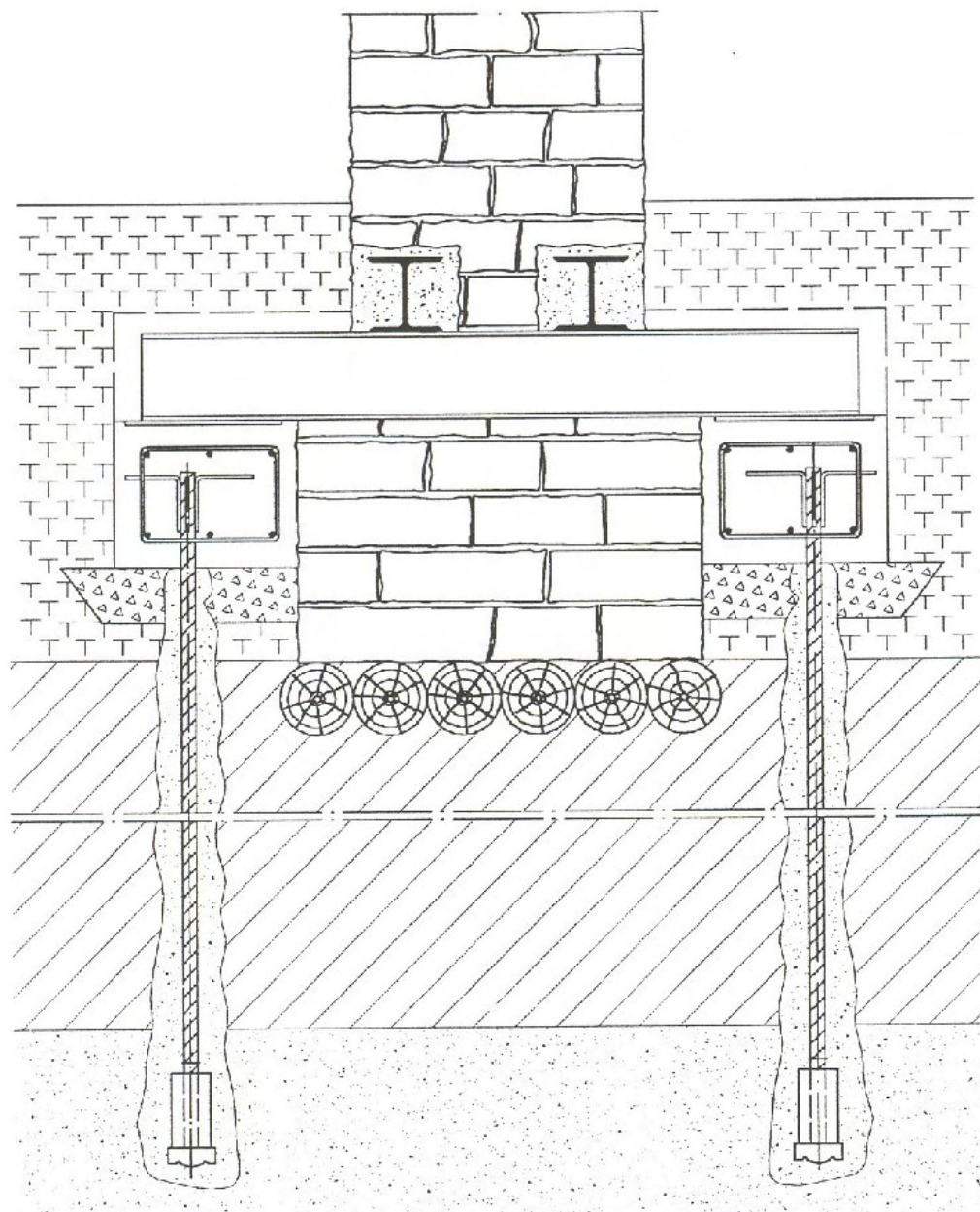


XII Puitvundamendid

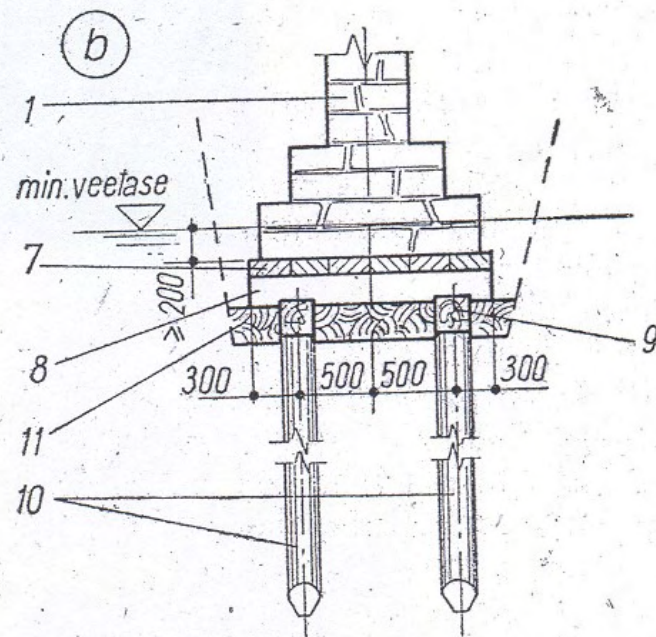
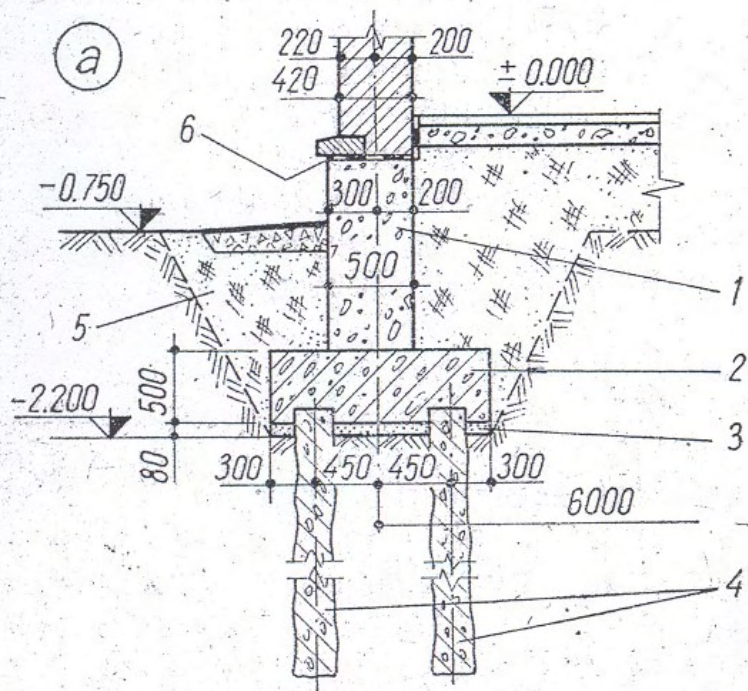
✓ Puitvundamendid:

- puitvaiadele ehitatud vundamendid
- puitparvedele ehitatud vundamendid

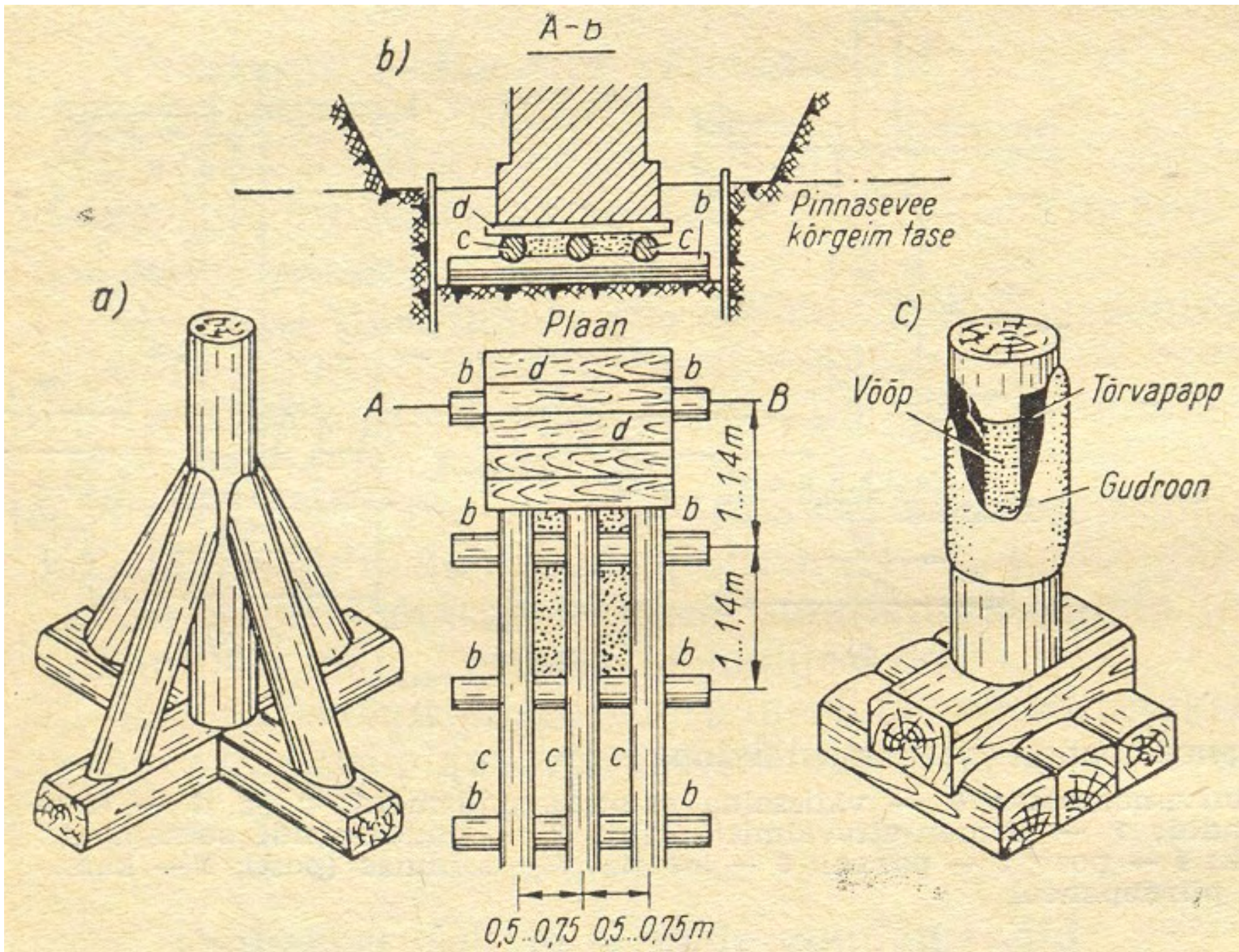
Seejuures võivad olla nii lint kui postvundamendid.



KAHELT POOLT TUGEVDAMIST VAJAVAT VUNDAMENTI SÜVITATAKSE VERTIKAALSELT MIKROVAIAD, VAIAD BETONEERITAKSE ROSTVÄRKI. KOORMUS ROSTVÄRKIDELE NING VAIADELE ANTAKSE ÜLE METALLTALADE ABIL



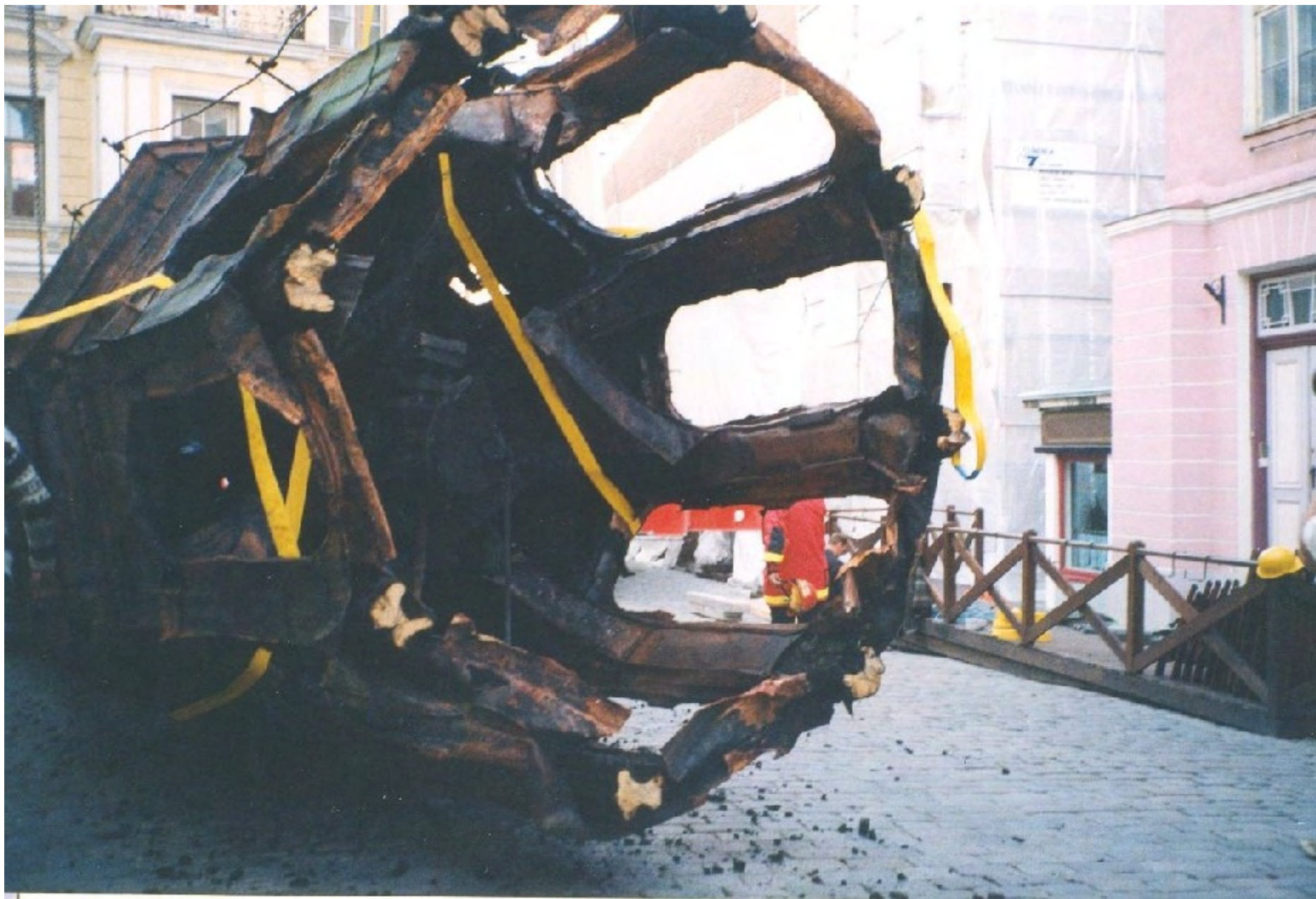
Joonis 3.6. Vaivundamendid: *a* — kohtvaiadega; *b* — puitvaiadega; 1 — vundament; 2 — raudbetoonpadi; 3 — liiv-
 alus; 4 — raudbetoonvaiad Ø 30 cm; 5 — tihendatud täitepinnas; 6 — kleefhüdroisolatsioon; 7 — laud 50 mm; 8 —
 põiktalad; 9 — pikitalad; 10 — puitvaiad Ø 18...30 cm; 11 — sav



XIII Puitkonstruktsioonide tulepüsisivus (*biopüsisivus* *vt hoonete ja ehitiste uuendamise kursuses*)

Tulekahju

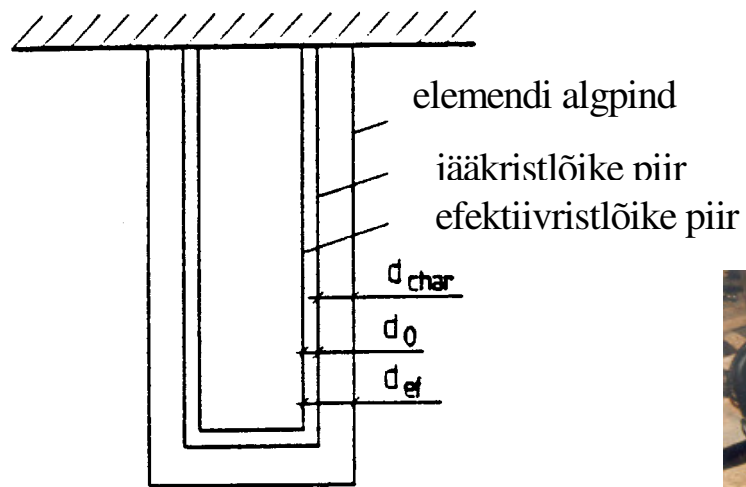








Tulepüsivus



*Toomkiriku
ebaõnnestunud
süütamiskatse*

Põlemiskiirused

Monoliitpuit 1,0 mm/min

Liimpuit 0,7...0,8

mm/min



Puit

A. Just “Puidu tulepüsivus”

...on põlev materjal!

- Puitu ei saa ühegi keemilise kaitsevahendiga muuta mittepõlevaks materjaliks.
- . Puitu võib muuta ainult raskelt süttivaks



Foto: J.Bregulla

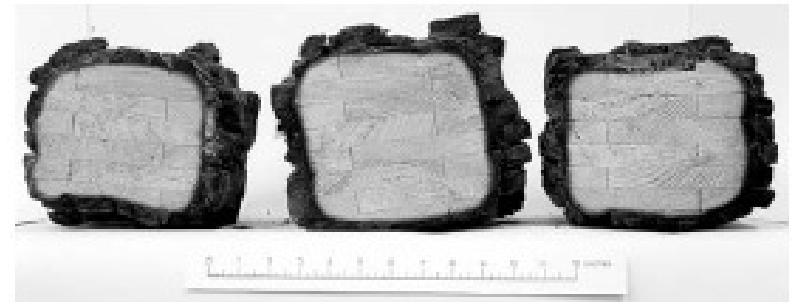
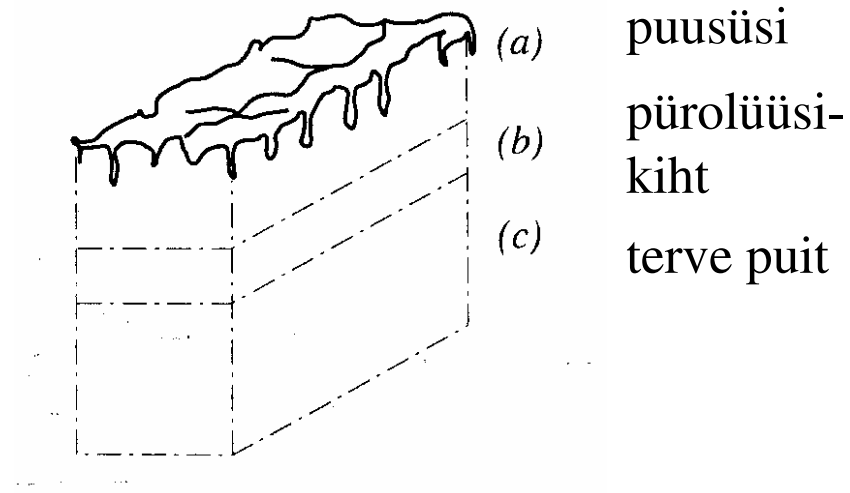
Puit

...on põlev materjal!

- Konstruksioonid süttivad esimesena väga harva.
- Põlemiskoormuseks on pigem sisustus, kaup jms

Puidu põlemine

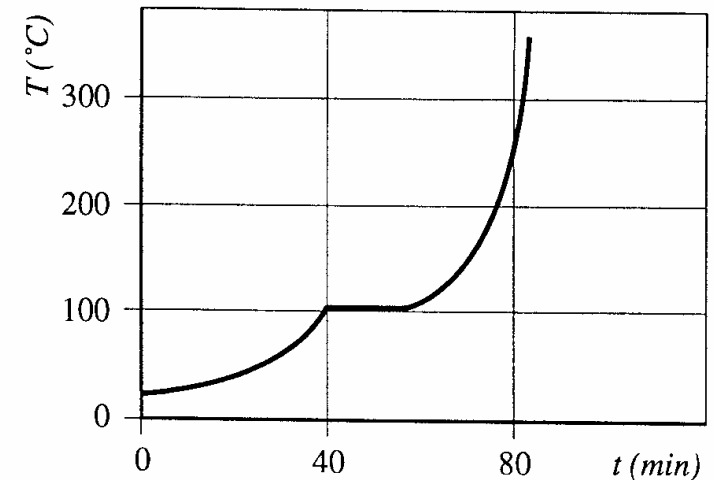
- Süttib leegist või suurest kuumusest (300..400⁰C)
- Moodustub isoleeriv puusöe kiht ning selle all pürolüüsikiht (ca 5 mm)





Puidu põlemine

- Pürolüüsikihi all hakkab vesi 100°C juures aurustuma
- Üle 200°C juures tekib rohkem põlevaid gaase ja CO_2 osa langeb
- Pinnatemperatuur tõuseb, pürolüüsikiht laguneb, karboniseerumine jätkub
- Üle 500°C juures on gaasi tootmine väike ja söe tootmine väga suur



Puidu põlemine

- **Puusöe soojusjuhtivus on ainult 1/6 puidu omast**
- Põlemata osal säilivad kõik kandevõime omadused v.a. vähenemine mõõtmetes.



Tulekahju

- **Standardtulekahju** on kolmeetapiline:
 1. Süttimisfaas, milles temperatuur tõuseb aeglaselt 400C-ni. See faas on inimeste turvalisuse kohalt otsustav ning asetab tarindite pinnakihtide süttivustundlikkusele suuremad nõuded. Kui temperatuur on tõusnud 500...600 C-ni, süttib kogu antud kohal olev aine korraga
 2. Põlemisfaas, milles temperatuur tõuseb 1100...1200 C-ni.
 3. Jahtumisfaas, milles kogu põlev materjal on põlenud ja temperatuur alaneb kiiresti.

Tulekahju

- Halli põleng kulgeb siiski teistmoodi, kui tulekahju madalates kohtades. Tuli ei levi plahvatuslikult üle kogu hoone, vaid jääb süttimiskohta. Tänu suuremale kõrgusele on õhuhulk suur ja temperatuuri tõus aeglane, kui näiteks eluruumides.
- Hallis süttinud tulekahju esineb tavaliselt kõrvalruumides ja puudutab harva kandekonstruktsioone.

Peale tulekahju

- Puittarindite kahjustusastme saab määrata piisavalt täpselt.
- Lühiajaline tulekahju ei ole võib-olla ohustanud tarindite kandevõimet, kuid on muutnud väljanägemist.
- Söestunud pinnakiht tuleb puhastada (liivapritsiiga) ja/või üleni kinni katta.
- Vajalik tarindi kandevõime tagatakse uue puidu lisamisega söestunud puidu asemele.

Peale tulekahju

- Ka kustutustöödel võib puitu kahjustada. Tõenäoline on konstruktsioonide märgumine.
- Tarindid tuleb hoolikalt kuivatada enne muude remonttööde teostamist.

Tuleohutus

- Passiivne tulekaitse
- Aktiivne tulekaitse
- Päästetööd

Tuleohutus

Põhiküsimusteks on alati inimeste turvalisus ja omandi kaitse.

- Hoone peab kestma teatud miinimumaja
- Tule ning suitsu tekkimine ja levimine hoones peab olema piiratud
- Tule levimine kõrvalasuvatesse hoonetesse peab olema piiratud
- Inimesed peavad tulekahju puhkedes saama hoonest väljuda või peab saama neid päästa
- Tähelepanu tuleb pöörata päästjate turvalisusele

Tuleohutusnõuded

Vabariigi Valitsuse määrus nr.315

“Ehitisele ja selle osale esitatavad tuleohutusnõuded”.

Kehtib alates 01.01.2005.a.

- Asendab suures osas EPN 10.1
- Lubab oluliste tuleohutusnõuete täitmise tõestamist ka arvutustega
- Lubab kasutada ka teiste riikide norme
- *NB. Määrused on kohustuslikud, standardid on vabatahtlikud*

Olulised tuleohutusnõuded

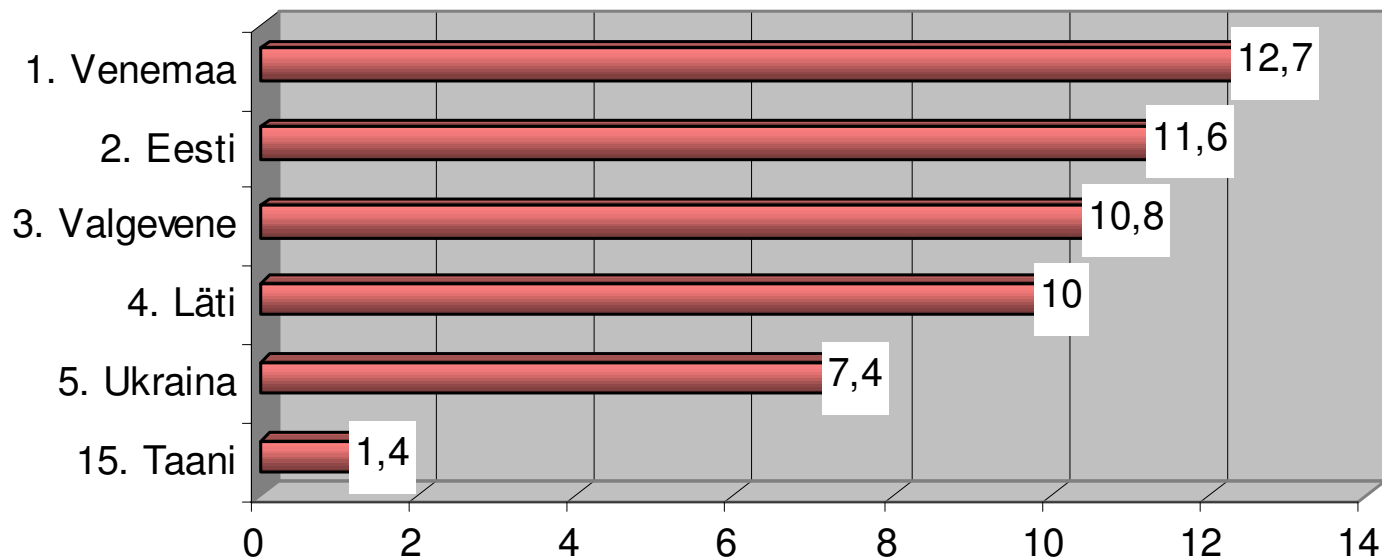
Määrus nr.315

- ehitis ja selle osa vastavad käesoleva määrusega ettenähtud piirväärtustele või
- ehitis ja selle osa vastavad asjakohasele tehnilisele normile või
- ehitis ja selle osa vastavad asjakohasele standardile või
- arvutuslikul, analüütilisel või muul usaldusväärsel viisil on tõestatud ehitise vastavus olulistele tuleohutusnõuetele, kusjuures on arvestatud tulekahju võimaliku puhkemise ja kustutamise.
- Asjakohaseks tehniliseks normiks ja standardiks käesoleva määruse tähenduses loetakse tehniline norm või standard, mille järgimine tagab oluliste tuleohutusnõuete täitmise.

Statistika:



**Tules hukkunute arv 100 000 elaniku kohta 2001 aastal
(CTIF raport nr 9)**



Tulepüsivusklassid

- TP-1 Suure tulepüsivusega
piirangud ei ole ehitise kõrgusele, korruste arvule, ega pindalale. Nõuded on konstruktsioonide tulepüsivusele ja tuleohutuspaigaldiste paigaldamisele.
- TP-2 Keskmise tulepüsivusega
piirangud kõrgusele ja korruselisusele ning inimeste arvule.
Ranged nõuded ehitismaterjalide tuletundlikkusele
- TP-3 Väikese tulepüsivusega
piirangud kõrgusele ja korruselisusele ning inimeste arvule ja ehitise kasutusviisile.
Kandekonstruktsioonile tulepüsivusnõudeid ei ole.

Tuleohutusnõuded

- Kandekonstruktsioonide tulepüsivus
- Ehitismaterjalide süttivustundlikkus

Tulepüsivusnõuded

Konstruksioonid peavad tulekahju korral:

- ära hoidma enneaegse varingu

Kandevõimekriteerium R_{xx}

- takistama tule levikut määratud piirkonda

Eraldavuskriteeriumid E_{xx} , I_{xx}

Tulepüsivusnõuded

Eralduvuskriteeriumid

- Tarindid peavad vältima kuumade gaaside ja leekide tungimist läbi tekkinud pragude või mulgustuse

Tiheduskriteerium E

- Tarindid peavad vältima temperatuuri tõusu üle lubatud piiri tulele mitteavatud pinnal

Isoleerivuskriteerium I

Tulepüsimisnõuded

R, E, I kriteeriumid



Kandevõime

R



Tihedus

E



Soojaisoleerivus

I

Puit kandekonstruktsioonides

- Kuni kahekorruselistes ehitistes võib puitu kandekonstruktsioonis kasutada piiranguta, sõltumata ehitise klassist
- 3-4 korruselistes TP-2 ja TP-3 kuuluvates elu-ja büroohoonetes võib puitu kandekonstruktsioonis kasutada piiranguta.
- Teistes tuletõkke-ja ehituskonstruktsioonides ning muudes ehitiseosades tuleneb puidukasutamine ehitusosale määratud tuletundlikkusest

TP 1

Kuni 2 korrust , R60...R120
Mittepõlev soojusisolatsioon

II ja III kasutusviis R60*...R120*
(Majutushooned, haiglad,
lastekodud, jms)

3...8 k. hoone R60*...R180*

* Tarind peab olema mittepõlevast materjalist

TP2 ja TP3

	TP2	TP3
Kuni 2k.hoone	R30	--
3, 4 k. hoone, I ja V kasutusviis (elamud, bürood jms)	R60	Ei lubata

Puidust ei tohi teha keldrikorruse
konstruktsioone

Tuletõkkesektsioonid

Piirpindalad, m²

	TP1,TP2	TP3
Eluhooned	<i>korter või eluruum</i>	
Majutushooned	800	400
Kogunemishooned, bürood	2400	400
Pööningud	1600	400
Keldrid	800	400

Materjali süttivustundlikkuse klassid

Euro klass	Suitsuklass	Põlevate tilkade klass	Nõuded vastavalt			Tüüpilised tooted
			Mittepõlevus		Väikeleek	
A1	–	–	x		–	Kivi, betoon
A2	s1 - s3	d0 - d2	x		–	Kipsplaadid, mineraalvill
B	s1 - s3	d0 - d2	–		x	Kipsplaadid, tulekindel puit
C	s1 - s3	d0 - d2	–		x	Kipsplaadi katted
D	s1 - s3	d0 - d2	–		x	Puit, puidupõhised plaadid
E	–	- or d2	–		x	Sünteetilised polümeerid
F	–	–	–		–	Nõudeid ei esitata

Puitmaterjalide euroklassid

Konstruksioonipuit

D-s2, d0

Liimpuit

Spoonplaadid, vineer

Puitkiudplaadid, $>900 \text{ kg/m}^3$

Puitkiudplaadid, $< 900 \text{ kg/m}^3$

E

Tsemendipõhised puitplaadid

B-s1, d0

Tuletundlikkuse nõuded

- Välisseinas üldjuhul:
 - TP-1 klass B- s1,d0 (va kuni 4 korruselises elu ja büroohoones)
 - TP-2 klass D-s2, d2 (3-4 korruseline elu ja büroohooned. Samuti ravi ja hooldusasutused)

Projekteerimisnormid

EN 1995-1-2 Eurocode 5 part 1-2 “Design of timber structures. Structural fire design”

Vahepeal kehtis:

EVS 1995-1-2:2003

“Puitkonstruktsioonid. Tulepüsivus”

On kehtiv:

EVS-EN 1995-1-2:2006. Puitkonstruktsioonide projekteerimine. Osa 1-2: Üldist. Tulepüsivusarvutus

EVS- EN 1995-1-2:2006

- Käsitleb puitkonstruktsioonide arvutamist tulekahjuolukorras
- Tulekaitsevärke jms **ei käsitle.**
- Aktiivse tuleohutuse meetodeid **ei käsitle.**

Tulepüsivusarvutus

Üldine tingimus

$$E_{d,fi} \leq R_{d,t,fi}$$

E – koormuse arvutuslik mõju

R – vastav arvutuslik vastupanu tulekahjuseisundis

$$E_{d,fi} = \eta E_d$$

η – koormuse vähendustegur tulekahjuolukorras

Tulepüsivusarvutus

Kandevõime kontroll:

- Elemendi arvutus
 - Efektiivristlõike meetod
 - Vähendatud tugevuse ja jäikuse meetod
 - Üldine arvutusmeetod

Koormused

Tulekahjukoormus on avariikoormuskombinatsioon!

- Ülekoormustegureid ei rakendata
- Normkoormuse vähendustegurid

Lumekoormus $0,2 s_k$

Tuulekoormus $0,5 s_k$

Kasuskoormus $0,3..0,8 q_k$

Tugevus ja jäikus

Arvutustugevus

$$f_{d,fi} = k_{mod,fi} f_{20} / \gamma_{M,fi}$$

$f_{d,fi}$ arvutustugevus
tulekahjuolukorras

$k_{mod,fi}$ modifikatsioonitegur

Arvutusjäikus

$$S_{d,fi} = k_{mod,fi} S_{20} / \gamma_{M,fi}$$

f_{20} tugevusnäitaja 20%-ne
fraktiil

$\gamma_{M,fi}$ materjali osavarutegur

$$\gamma_{M,fi} = 1$$

Tugevus ja jäikus

$$f_{20} = k_{fi} f_k$$

$$S_{20} = k_{fi} S_{05}$$

k_{fi} teisendustegur, mis sõltub materjali variatsioonitegurist
 f_k normtugevus
 S_{05} jäikuse 5% väärtus (E, G)

k_{fi} väärtused

Saepuit 1,25

Lamell-liimpuit 1,15

Spoonliimpuit(Kerto) 1,1

Söestumissügavus

Söestumine ühest küljest

$$d_{\text{char,o}} = \beta_0 t$$

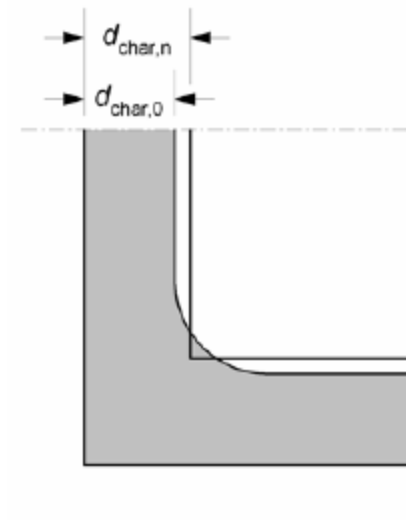
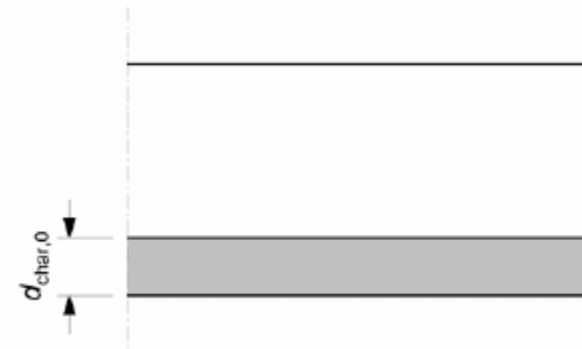
t aeg minutites

β_0, β_n söestumiskiirus

Söestumine mitmest küljest

Tinglik söestumissügavus

$$d_{\text{char,n}} = \beta_n t$$



Söestumiskiirused

	β_o , mm/min	β_n
Okaspuit		
Liimpuit	0,65	0,7
Saepuit	0,65	0,8
Lehtpuit		
normtihedus 290 kg/m ³	0,65	0,7
normtihedus üle 450 kg/m ³	0,5	0,55
Spoonliimpuit	0,65	0,7

Söestumiskiirused

Söestumiskiirust β_o võib kasutada, kui ristlõike vähim mõõde on suurem kui

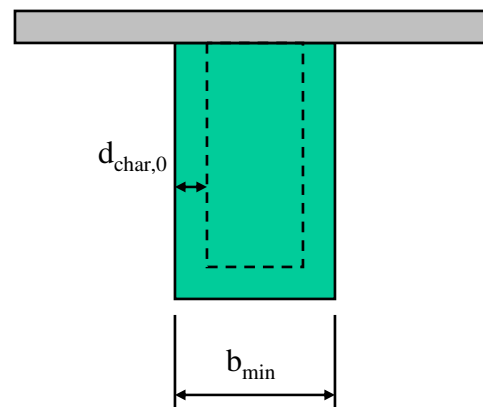
$b_{\min} =$

$$2d_{\text{char},n} + 80$$

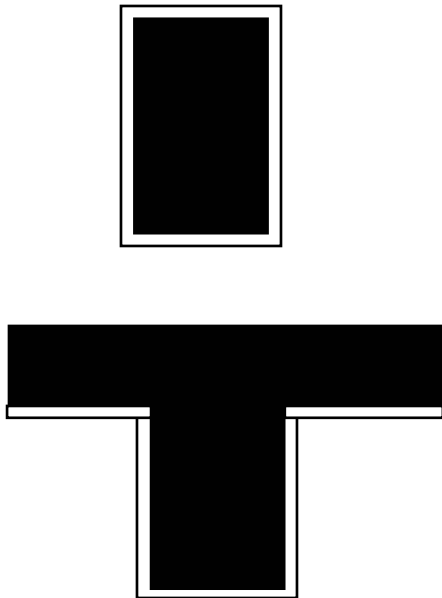
kui $d_{\text{char},0} \geq 13 \text{ mm}$

$$8,15d_{\text{char},n}$$

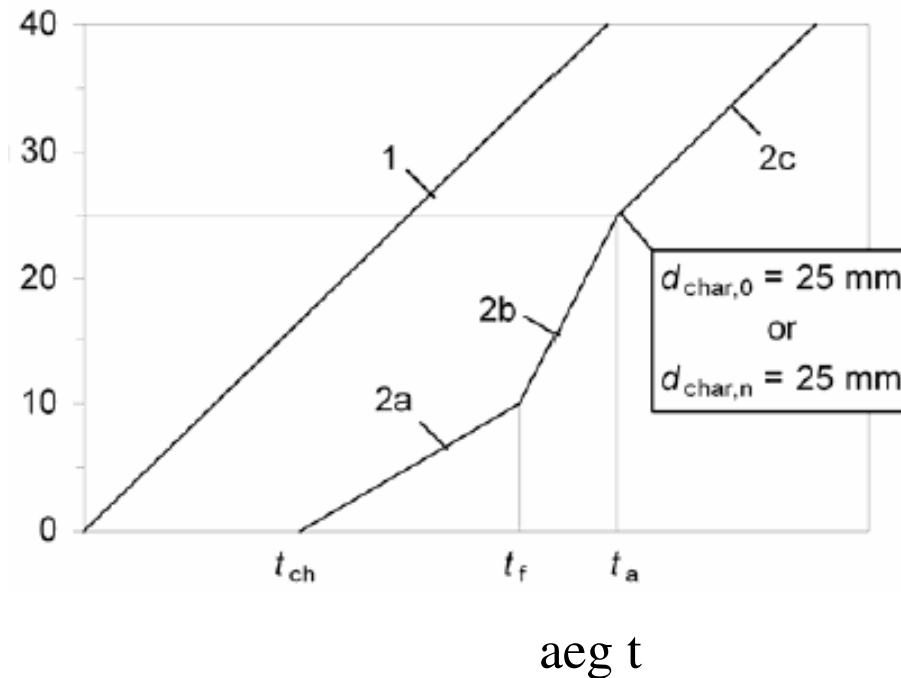
kui $d_{\text{char},0} < 13 \text{ mm}$



Kaitstud pinnad



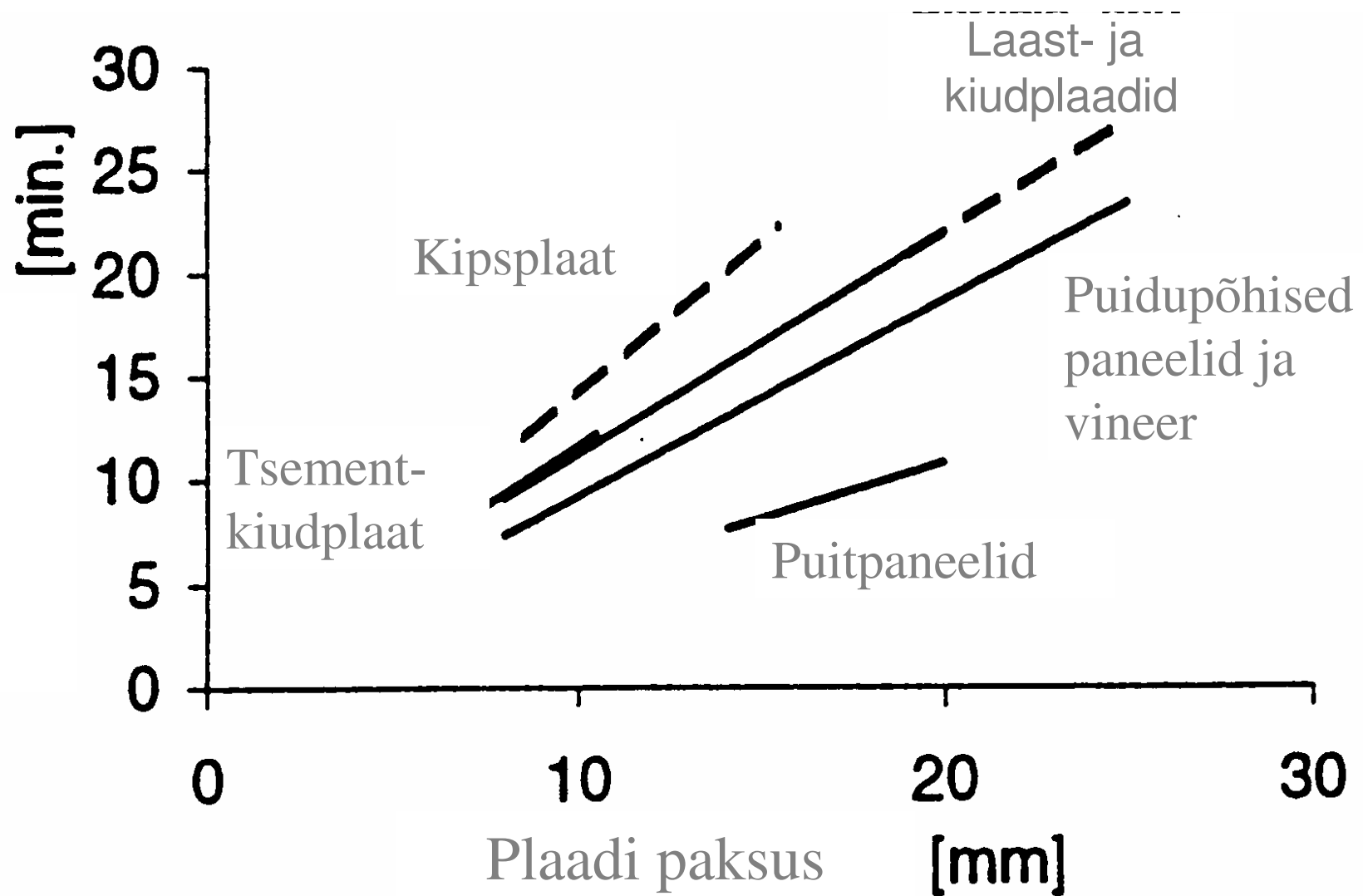
$d_{\text{char},0}$
või
 $d_{\text{char},n}$
[mm]



t_{ch} söestumine algab
 t_{f} kattematerjal puruneb
 t_{a} söestumissügavus 25 mm

1 kaitsmata pind
2a kattematerjal jääb veel paigale
2b kattematerjal on ära kukkunud
2c söestumiskiirus ühtlustub
kaitsmata puidu s.k.-ga

Plaadi paksus ja tulepüsivus

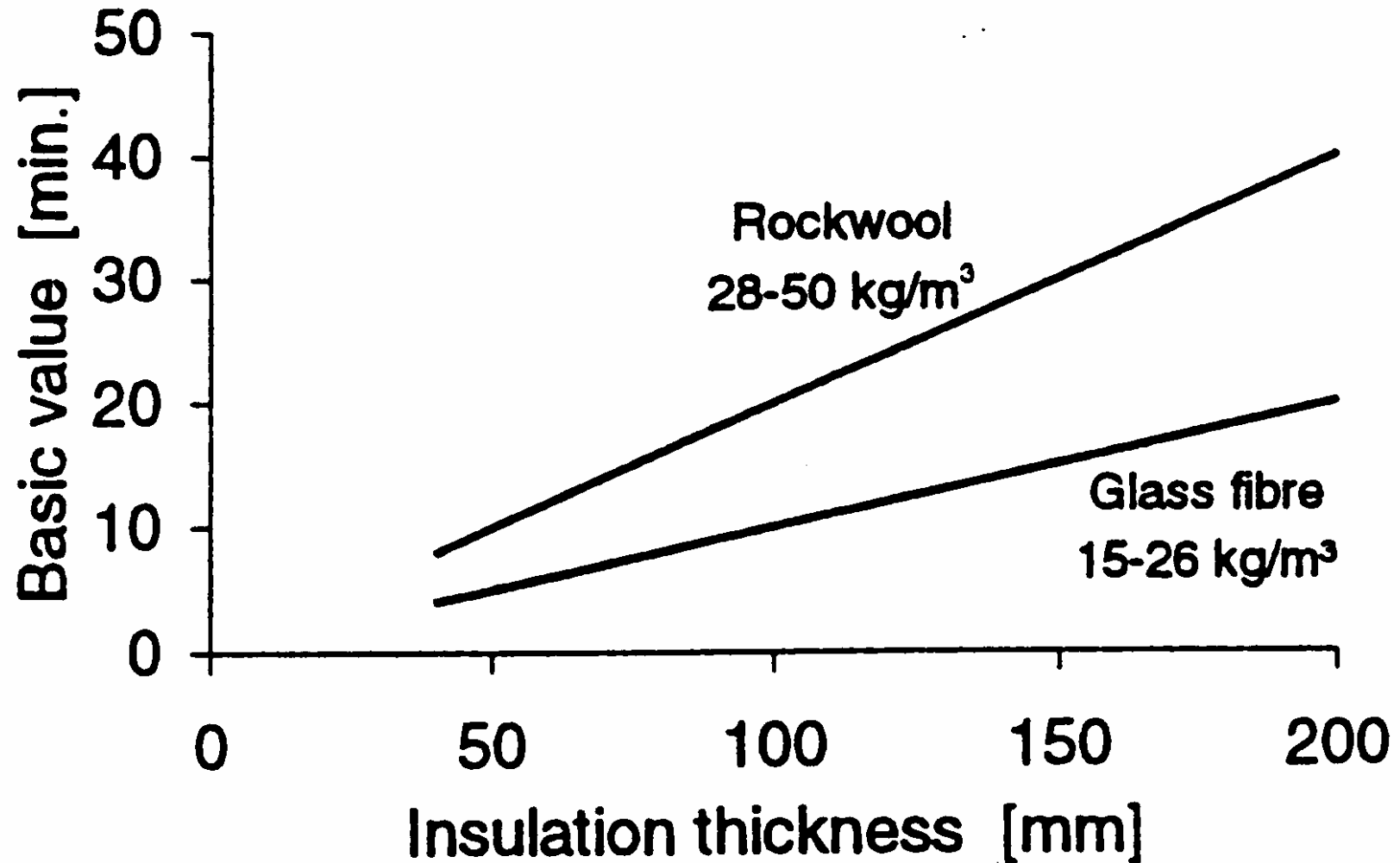


Kaitstud pinnad

t_{ch} määramine

- Puitplaadid $t_{ch} = h_p / \beta_0$
 - Kips $t_{ch} = 2,8h_p - 14$
 - Kivivill $t_{ch} = 0,07(h_{ins} - 20) (\rho_{ins})^{0,5}$
-
- Võõpasid normis ei käsitleta
 - Puuduvad andmed kõikide kipsplaadi tüüpide kohta

Isolatsiooni paksus tõstab tulepüsivust



Efektivrastlõikemeetod

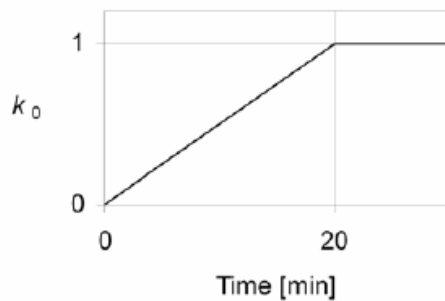
Efektivsöestumissügavus

$$d_{ef} = d_{char,n} + k_0 d_0$$

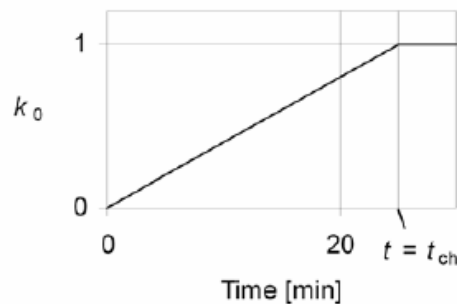
$$d_0 = 7 \text{ mm}$$

$$k_{mod,fi} = 1$$

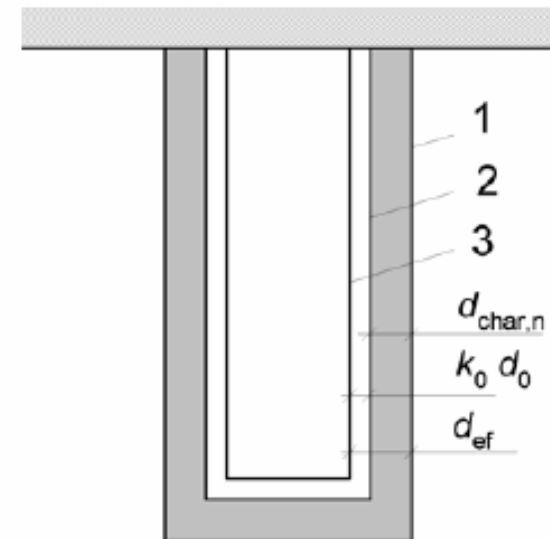
k_0



Kaitsmata pind



Kaitstud pind



- 1 ristlõike algne pindala
- 2 jääristlõike piir
- 3 efektivrastlõike piir

Efektivristslõike meetod

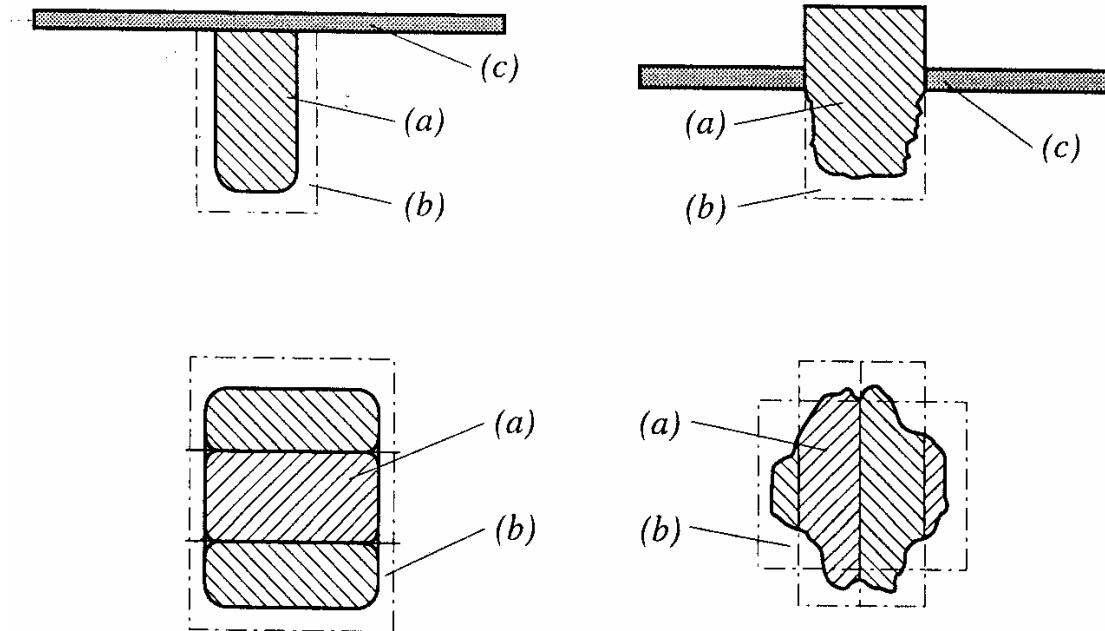
Efektivsügavus
(kaitsmata pinnad)

		d_{ef} , mm		
	R30	R60	R90	
Saepuit	31	55	79	
Liimpuit	28	49	70	



Efektivrislõike meetod

- Teostatakse kandevõime kontroll leitud tugevuste, koormuste, ristlõigetega



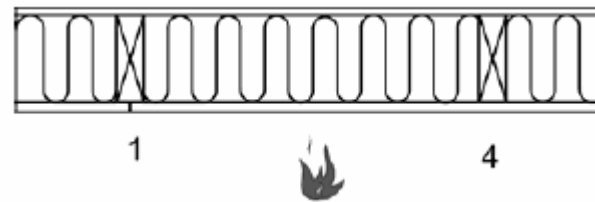
Lihtsustused

- Kui elemendi jäikusside tulekahjus puruneb, siis sellega ei arvestata
- Ristikiudu survet ei pea arvestama
- Täisristlõike puhul võib nihke jätta arvestamata

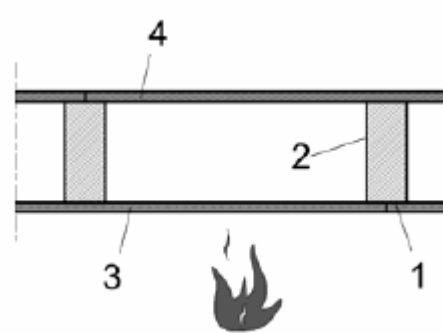
- Deformatsiooniarvutus tuleb teha vaid juhul, kui vastavate elementide tootekirjeldustes nõutakse kandekonstruktsioonide deformatsioonide arvestamist

Seinad ja vahelaed

- Isolatsiooniga täidetud seinad ja vahelaed
 - Juhised lisas C



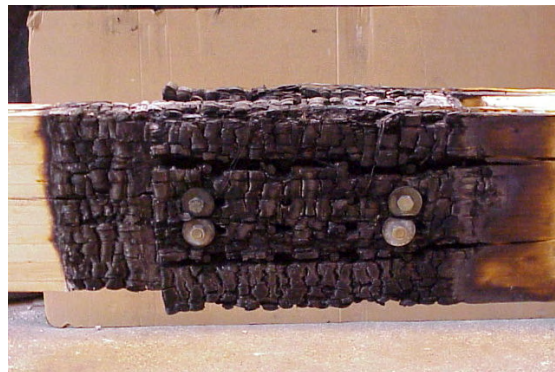
- Tühimikega seinad ja vahelaed
 - Juhised lisas D



- Arvutus eralduskriteeriumile
 - Juhised lisas E

Liited

Puit puiduga



Teras puiduga



Fotod: P.Racher

Liited

- EN 1995-1-1 järgi projekteeritud kaitsmata “puit-puiduga” liidete tulepüsivus

	$t_{d,fi}$, min	piirtingimus
naelad	15	$d \geq 2,8$ mm
kruvid	15	$d \geq 3,5$ mm
poldid	15	$t_1 \geq 45$ mm
naaglid	20	$t_1 \geq 45$ mm

t_1 – äärmise elemendi paksus

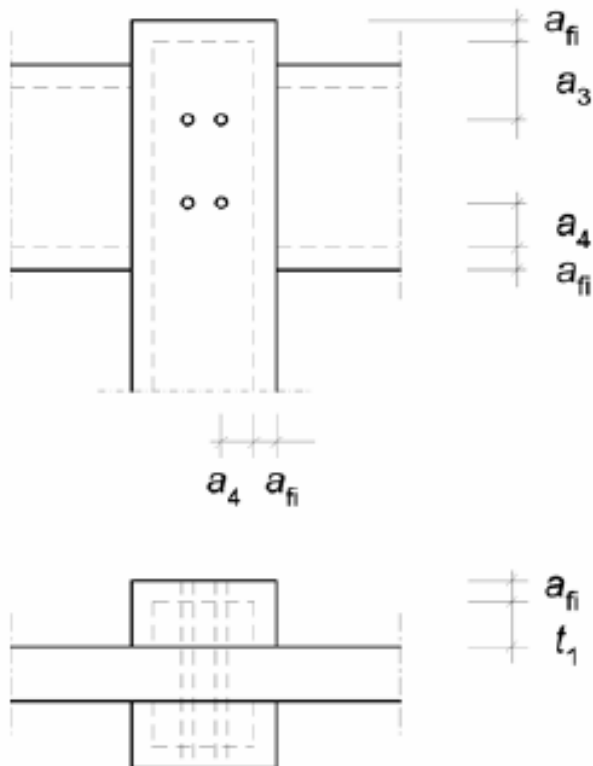
Liited

Suurema tulepüsivuse saavutamiseks

- Suurendada nõutud kaugusi a_{fi} võrra
- Vähendada koormust teguri η võrra
- Või teha mõlemat

Liited

- Tulepüsivus $t_{d,fi}$ kuni 30 min
 - Nõutud kaugusi suurendada a_{fi} võrra



$$a_{fi} = \beta_n k_{flux} (t_{req} - t_{d,fi})$$

β_n söestumiskiirus

k_{flux} soojuse kandumist läbi kinniti arvestav tegur

$$k_{flux} = 1,5$$

t_{req} nõutav tulepüsivusaeg

Liited

Kaitstud liited

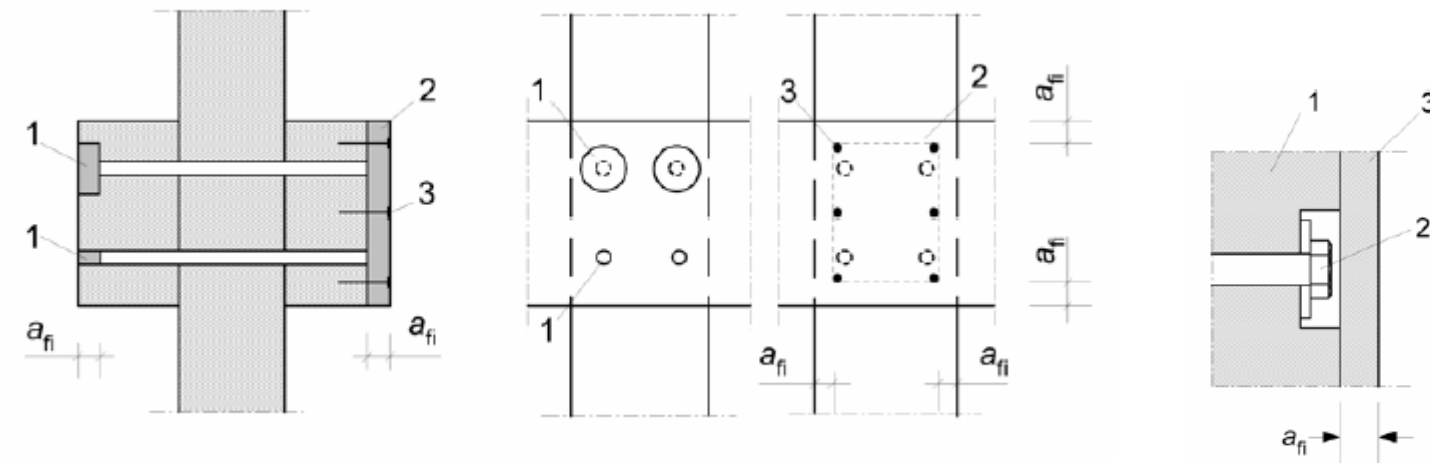
- Puidu või kipsplaadiga (tüüp A,H)
- Kipsplaadiga (tüüp F)
- Sisseliimitud korkidega

$$t_{ch} \geq t_{req} - 0,5 t_{d,fi}$$

$$t_{ch} \geq t_{req} - 1,2 t_{d,fi}$$

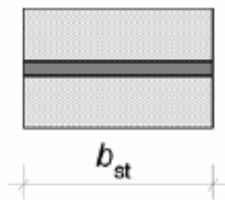
$t_{d,fi}$ - kaistmata liite
tulepüsivus tabelist

(15-20 min)

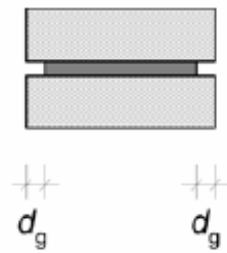


Liited

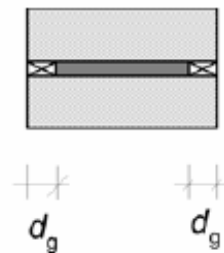
Sisemised terasplaadid



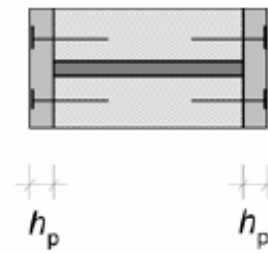
Kaitsmata



*Kaitstud
piludega*



*Kaitstud
korkidega*



*Kaitstud
plaatidega*

Tulepüsus

b_{st}

R30

≥ 200 mm

R60

≥ 280 mm

Liited

Liimid

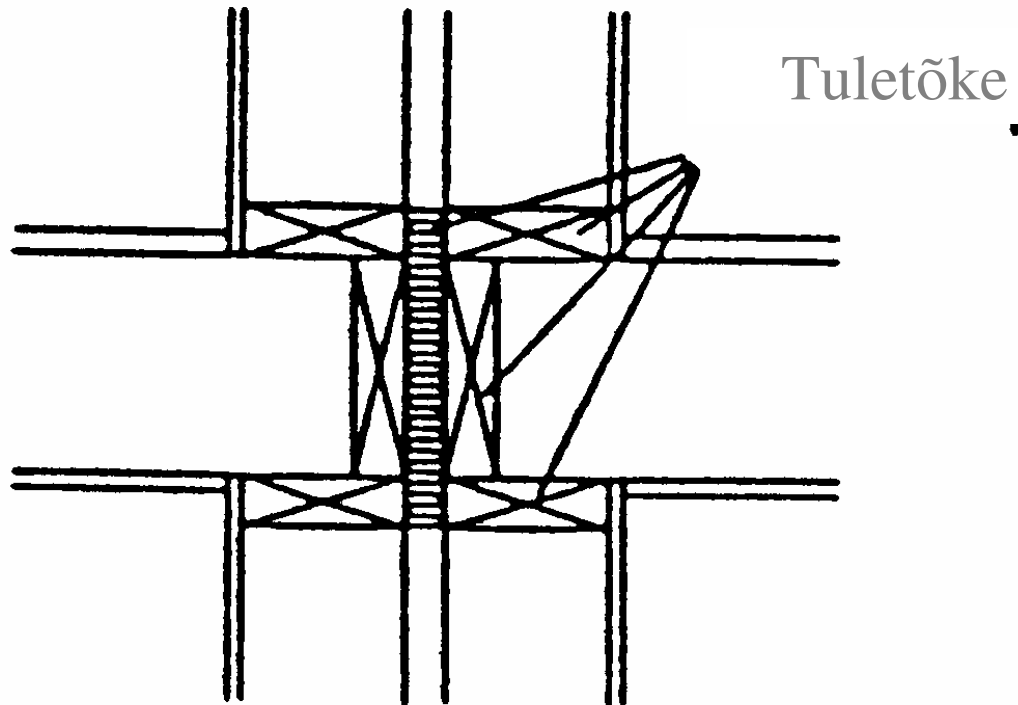
- Fenool-formadelhüüd ja aminoplastliimid, mis vastavad EN301 ja EPN 5.1.1 nõuetele, tagavad liite terviklikkuse nõutava tulepüsivusaja kestel

Detailid

- Tuletõkked**
- Ventilatsioonivad**
- Pööningu eraldamine**

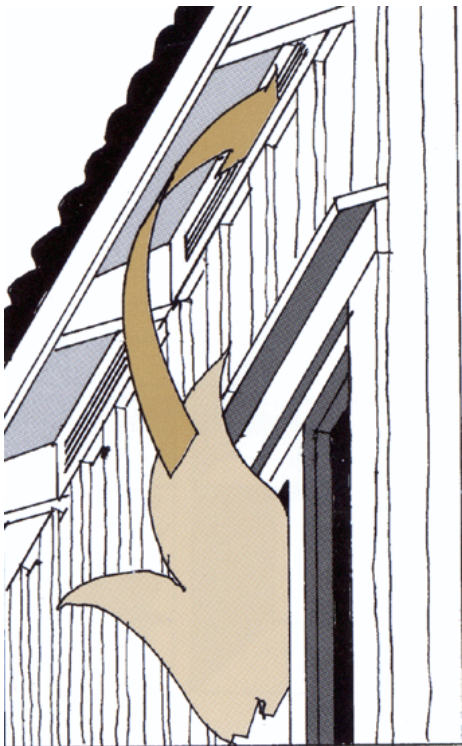
Tuletõkked

Põranda ja seina ühendus



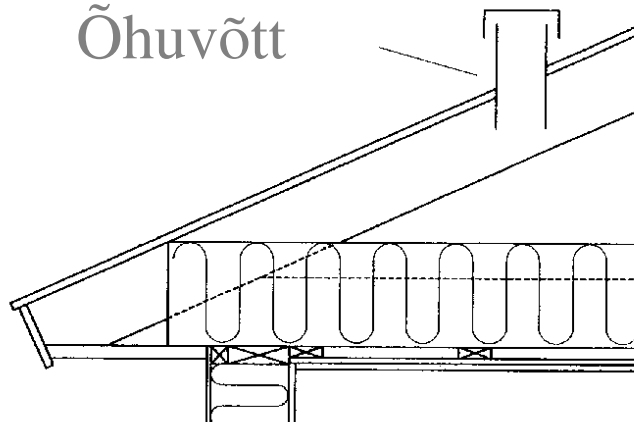
Õhuavad räästas

Risk tule levikule



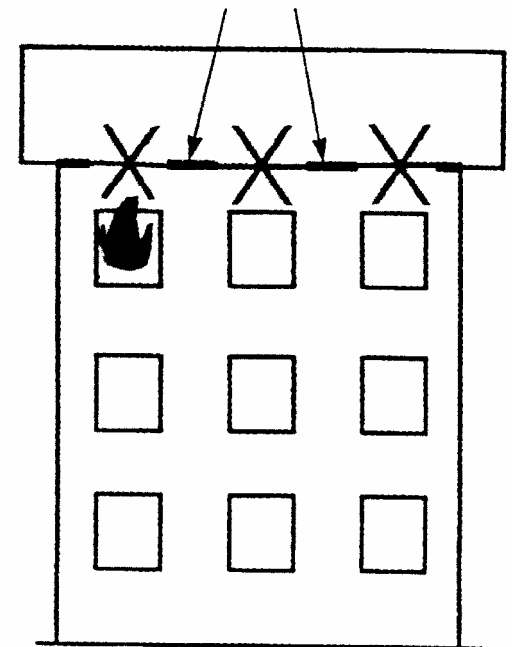
Ventilatsioon katusel

Õhuvõtt

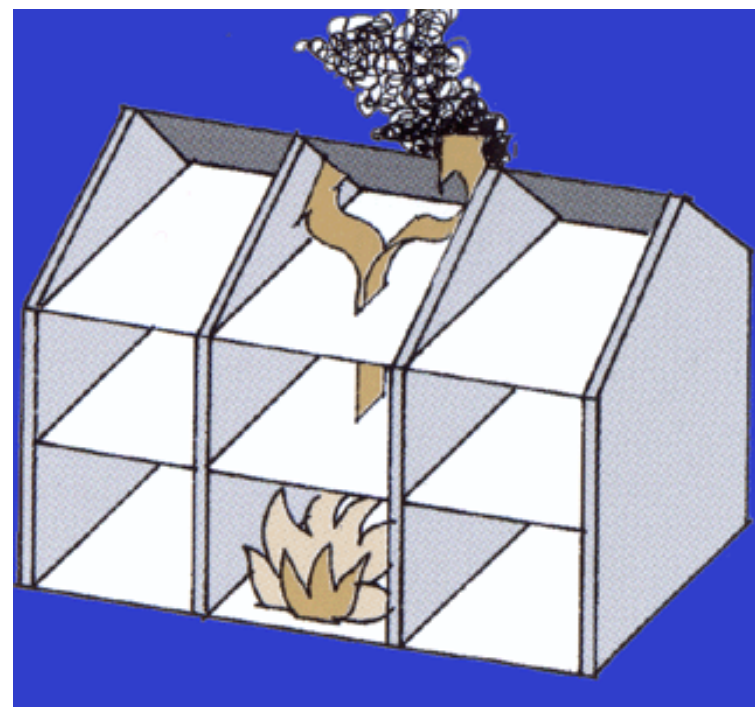


MITTE akna kohal!

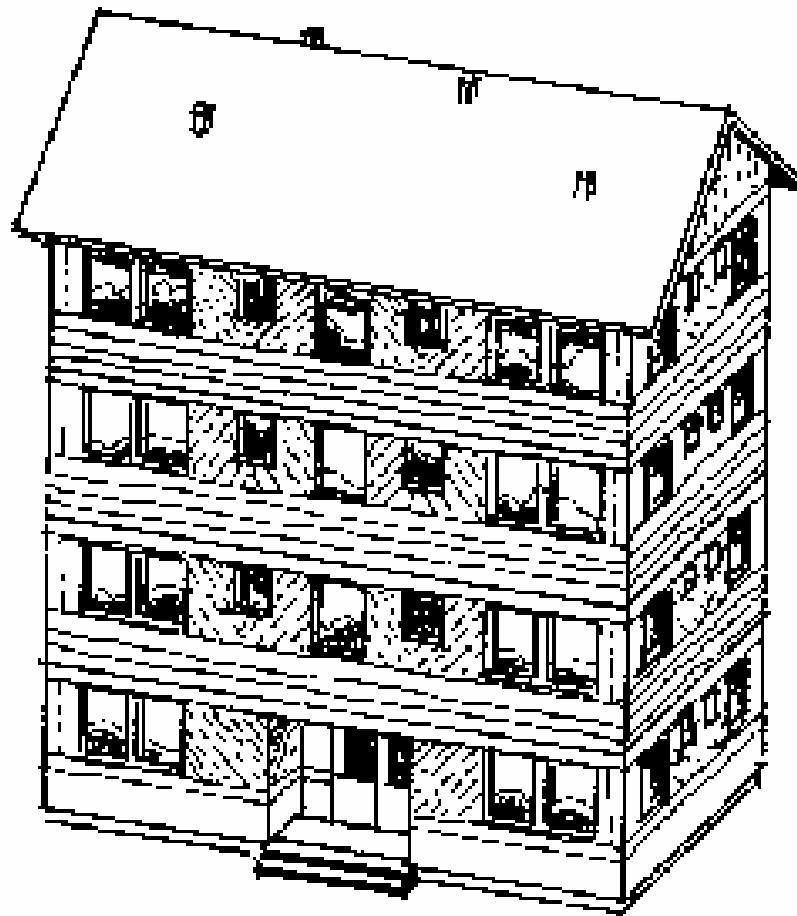
Ventilatsiooniavad



Pööningu eraldamine

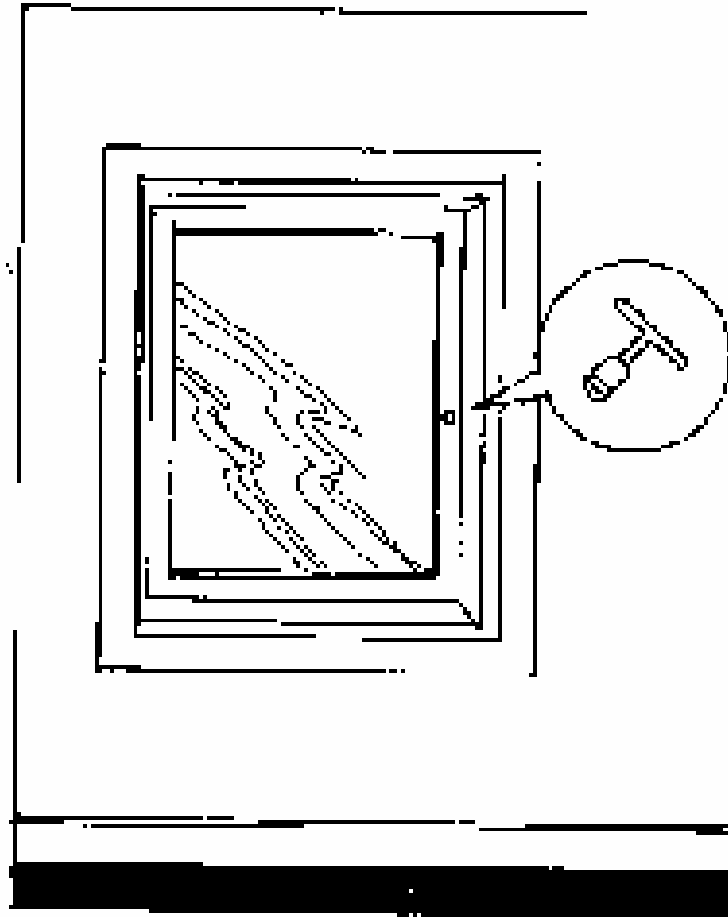


Osaline puitfassaad



SP Träteknik

Tulekindlad aknad



Aktiivne tulekaitse



Sprinkler

60 minutit põlenud tala

*Kaufmann Holz
Liimpuidu tehas
Austria*



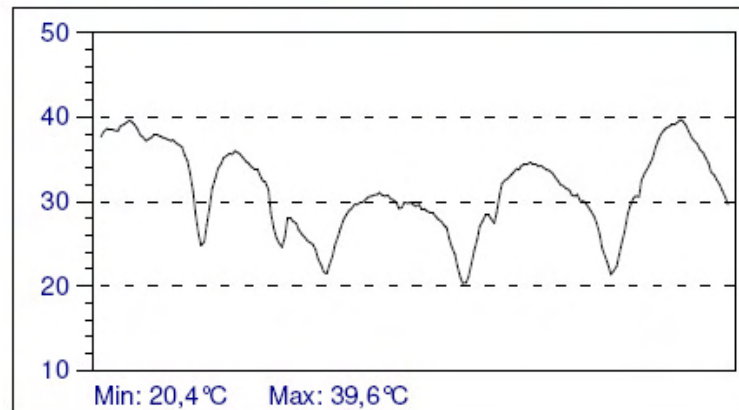
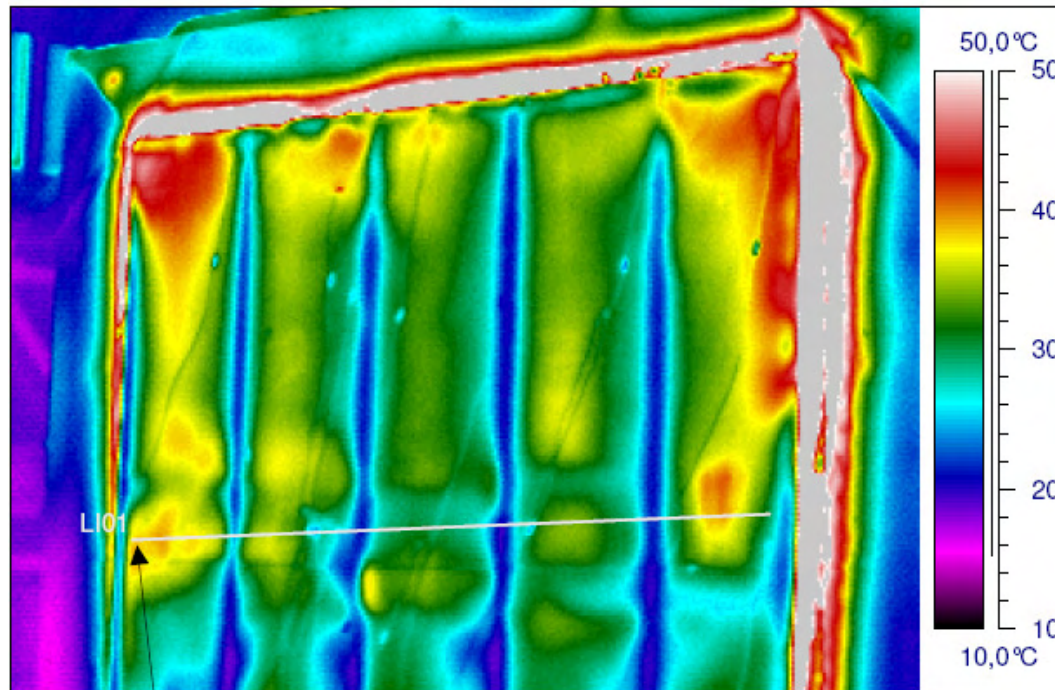
Paneeli tulepüsivuse määramine laborikatsetega



Tulepüsivuse määramine laborikatsetega



Tulepüsivuse määramine laborikatsetega



Restoran "Paat"



TP 2
Liimpuit R30
Vahelagi betoonist

Valmis: 2001

Maks sildeava: 10 m

“Estonia” kuppelsaal



Sildeava: 14 ja 18 m
Kaarte samm: 4 m

TP 1
Liimpuit R60
Teras kaitstud puiduga



Liimpuitehitised



Liimpuit R60
Ühendused kaetud
puitlappidega

Vierumäki, Soome

Lillehammer OM 1994



Vikingskipet, Hamar



•Avad kuni 120 m

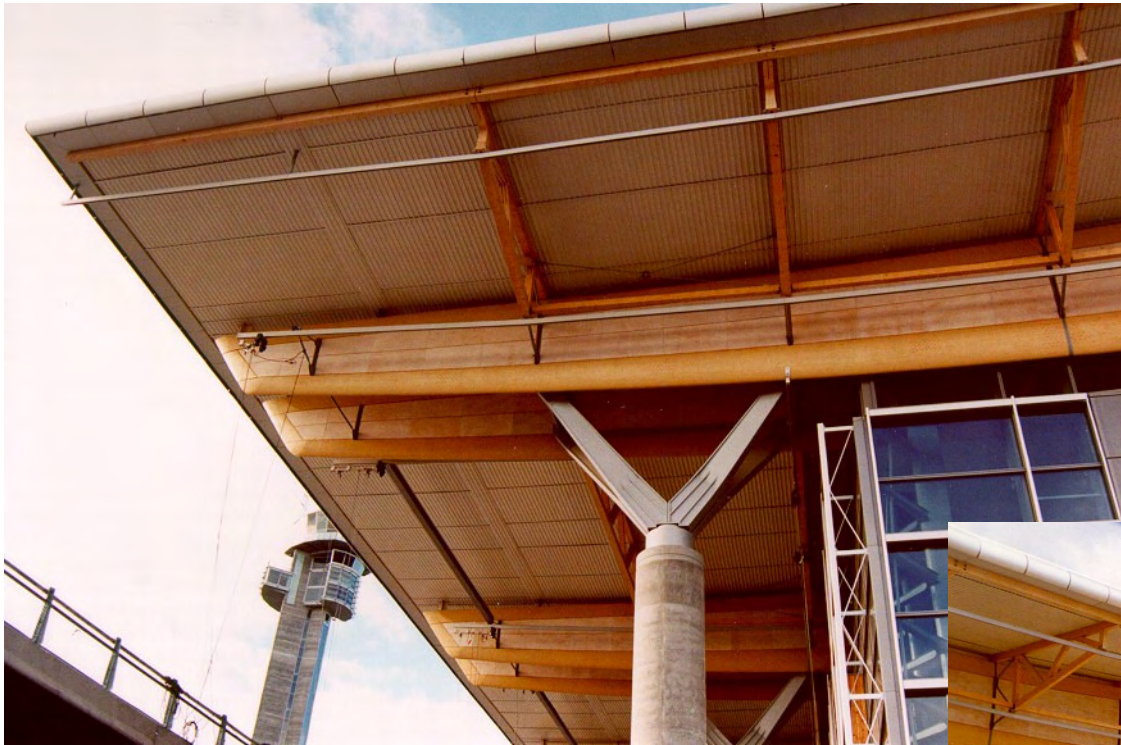
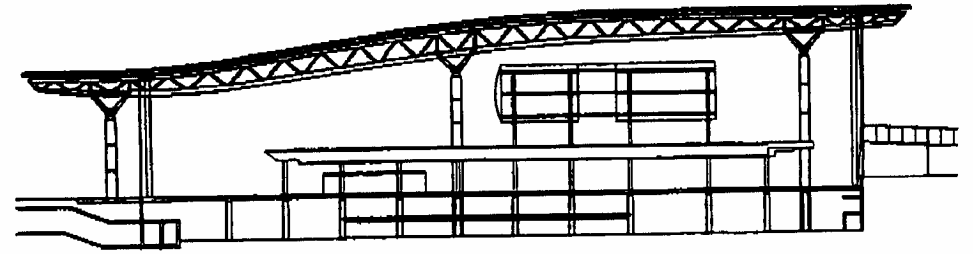


Håkon's hall, Lillehammer



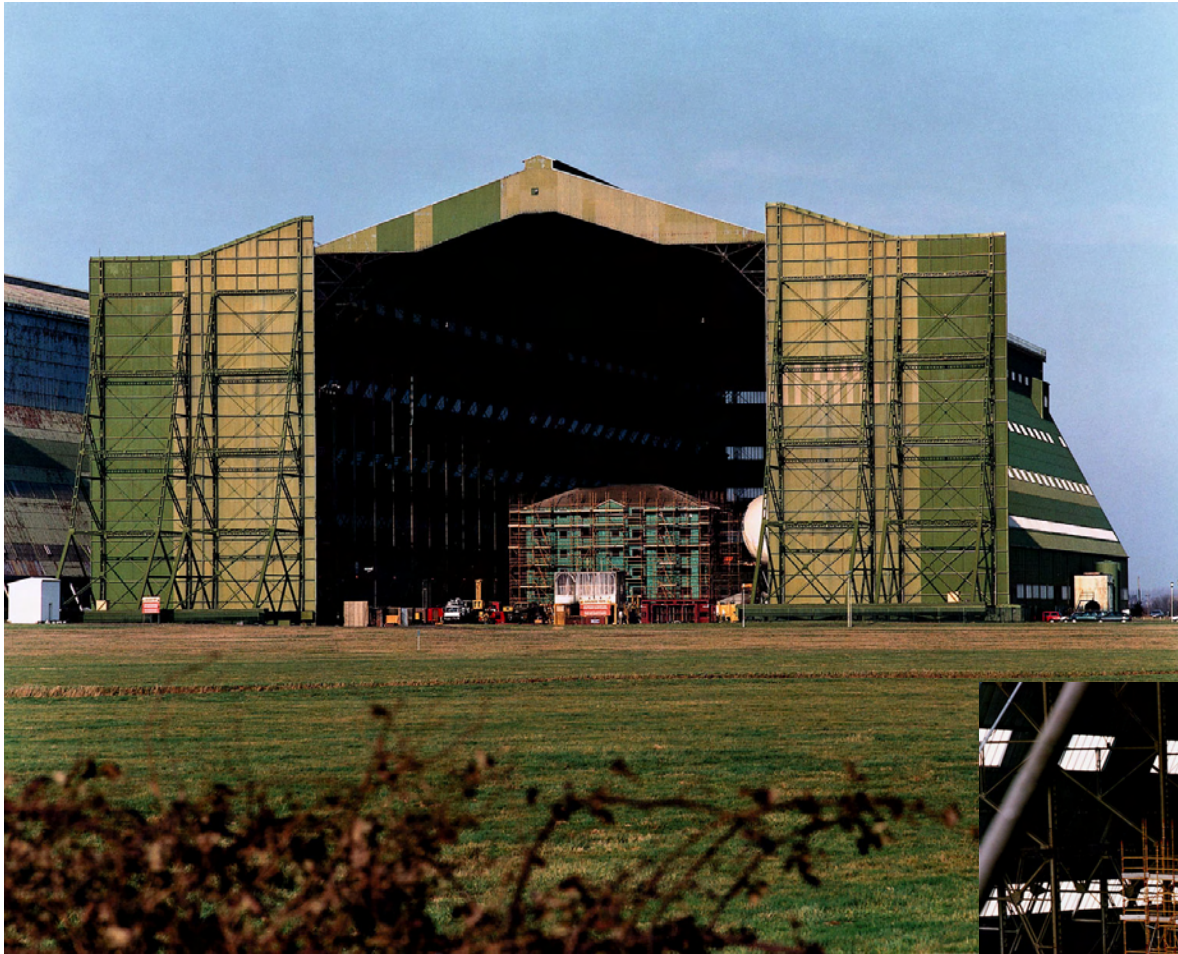
R 120
Teras kaitstud puiduga

Gardermoen'i lennujaam Oslos



R 120

Teras kaitstud puiduga



BRE Cardington

Angaari ehitatud katsemajad



Puidust korrusmajad



Wälludden, Rootsi



Lahti, Soome

Ylöjärvi, Soome



Lotsen, Rootsi

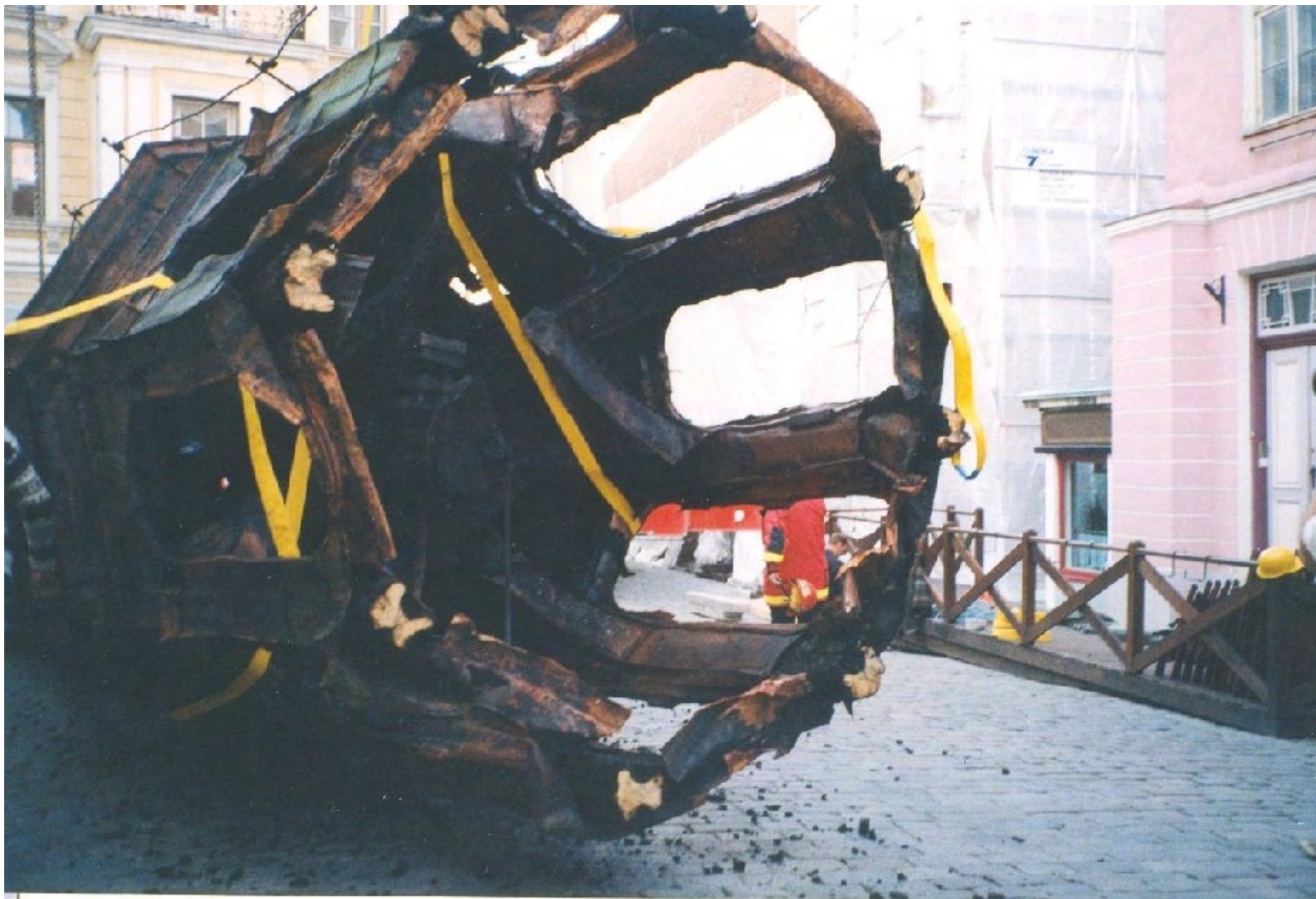


Püha Vaimu kiriku põleng

29.05.2002











Püha Vaimu kiriku põleng











Kokkuvõte

- **Puidust saab tulepüsivalt ehitada**
- Mittepõleva materjali nõue ei ole alati õigustatud
- Tavaliselt ei ole suuresildeliste konstruktsioonide puhul vaja ristlõiget tulepüsivuse eesmärgil suurendada.
- Tähelepanu tuleb pöörata liidetele
- Veel puidu tulepüsivusest:

www.puuinfo.ee

www.fsuw.com

FSUW raport

FSUW -Fire Safe Use of Wood



Eestist:

Märt Riistop
Eesti Metsatööstuse Liit

Alar Just
AS Resand



Roadmap 2010 Building with Wood -Fire-

Fire safe use of wood
State-of-the art study

Julie Bregulla
Coordinator of FSUW network



Some findings- Task 1 Overview Building regulations in Europe

Building application	Number of storeys allowed in different countries													
	AT	CZ	EE	FI	FR	DE	IT	LV	NL	PL	ES	SE	CH	UK
Number of storeys (without sprinklers)	3-4		4	2	∞	5	(∞)		(∞)	3-4	∞	∞	6	∞
Wood façade claddings (without sprinklers)	1-2		8	2	∞	3	(∞)		(∞)	3-4	(∞)	2	3	∞
Interior wood linings - in flats	∞		∞	(∞)	∞	∞	(∞)		(∞)	∞	no	2	8	no
- in escape routes	no		∞	no	∞	3	(∞)		(∞)	no	no	no	no	no
Wooden floorings - in flats	∞		∞	∞	∞	∞	(∞)		(∞)	∞	no	∞	8	∞
- in escape routes	no		∞	∞	∞	∞	(∞)		(∞)	∞	(∞)	∞	8	(∞)
Differences with sprinklers	no		yes	yes	yes	no	(no)		(no)	no	no	yes	yes	yes

	≥ 5 storeys in timber structure or with wood product OR <u>few limitations</u> to use wood
	3-4 storeys in timber structure or with wood product OR <u>medium limitations</u> to use wood
	≤ 2 storeys in timber structure or with wood product OR <u>major limitations</u> to use wood



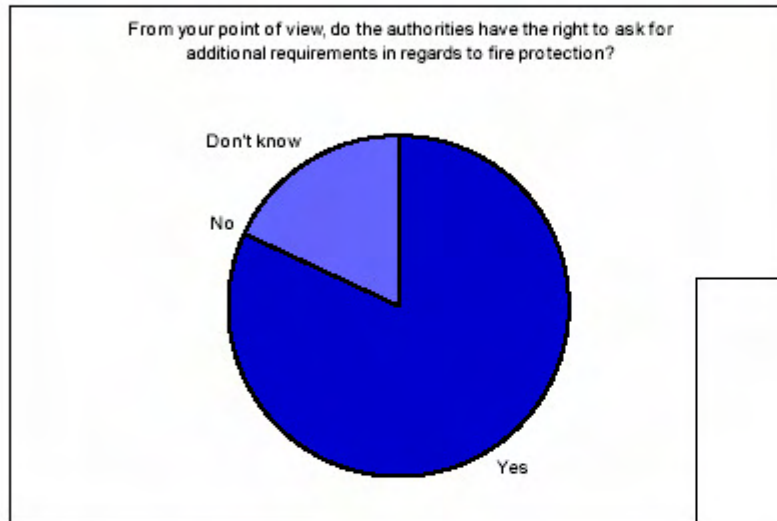
Some findings- Task 1 Overview Building regulations in Europe

Key features of regulatory system

Key features:	
- Performance based design (material independent)	4 countries: IT, NL, SE, CH
- Prescriptive design	5 countries: AT, FR, DE, PL, ES
- Both	3 countries: EE, FI, UK
Changes in building regulations since 2000 (excl introduction of new European classes)	2 countries: EE, CH
Possible changes in building regulations foreseen (in relation to wood products)	6 countries: AT, EE, FI, DE, IT, ES
New possibilities with performance based design (in relation to wood products)	Most countries, but expressed mainly by 5 countries: AT, EE, FI, IT, ES
Local or regional interpretations	Mainly in 5 countries: AT, (FI), DE, (ES), CH



Some findings- Task 2 Local interpretations and influences



Germany

Have authorities the right to ask for additional requirements for fire protection?

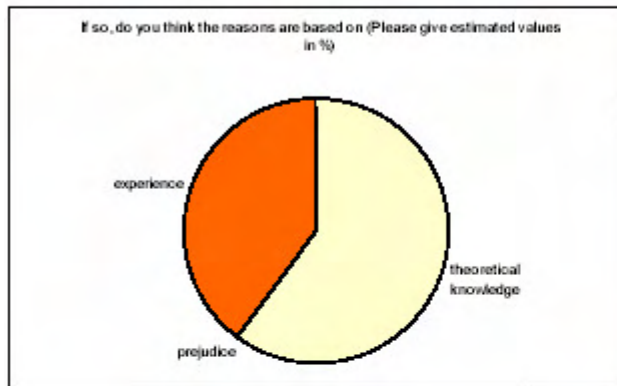


UK

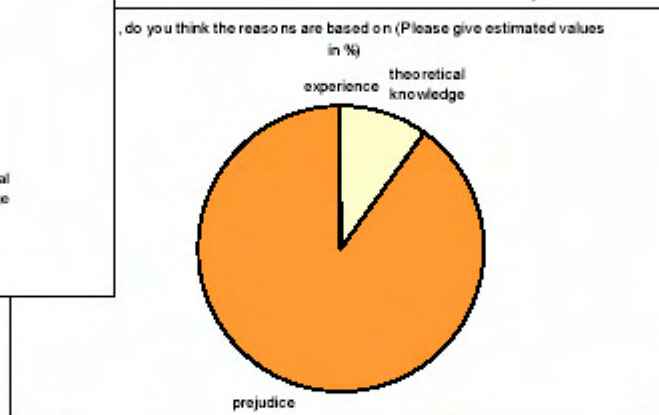


Some findings

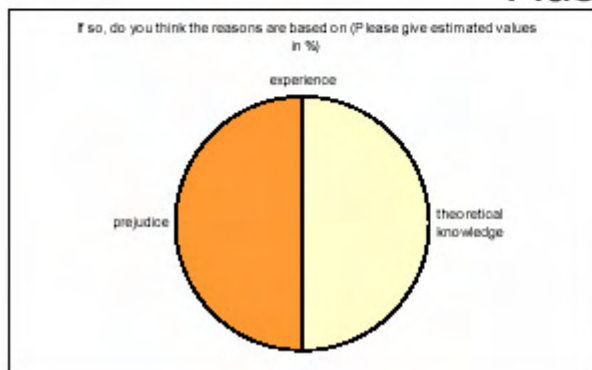
Why do you think this is seen as a problem?



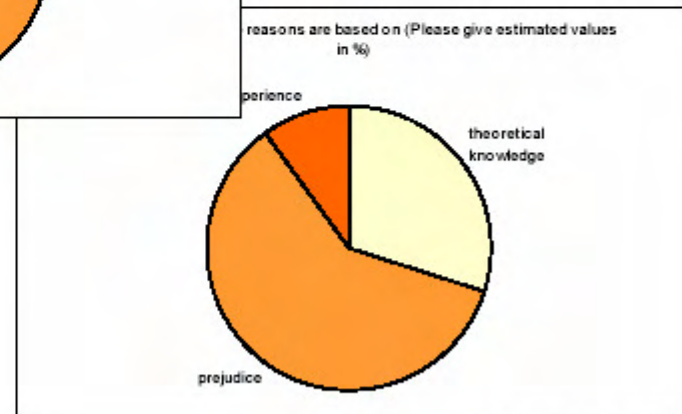
Estonia



Austria



Sweden



France



FIRE Feasibility study

What is clear

- Some limitations are posed by regulations (different limitations depending on country)
- In the majority of European countries any material is accepted as long as the functional requirements can be met- guidance on acceptable engineering solutions is missing.
- In the majority of European countries the scope for timber products given in current regulations is not fully exploited
- The use of wood is therefore to greatest extent restricted by
 - Impact of local and regional interpretation of fire regulations.
 - Lack of knowledge, both building regulation officers and fire brigades
 - Lack of knowledge by practicing structural engineers and architects
 - Lack of detailed knowledge to allow fire safety engineering approach
 - No data proving adequacy of timber solutions in some applications.
 - Lack of guidance documents
- Supporting research is available and ongoing, areas for further research have been identified.
- Available knowledge must be more widely spread and adapted to European dimension
- As most European countries are increasingly moving to performance-based design it is important that European Application Documents are produced, also guiding in national implementation.

What is open

- Provide information that can support lobbying efforts on wider scale
- Change attitudes: Gather strong evidence for support and marketing
- Lobby government departments based on evidence

XIV Plastehituskonstruktsioonid, eriti kangas- konstruktsioonid (sh telk- ja pneumokonstruktsioonid) ja arvutamise iseärasused

Looduslikud kiudained:

- Puuvill. Kasutamine: Riil (s.h. tehnoorie, näit kirsas, kotirii, niit, nõõr, kõis, kalavõrk)
- Lina. Kasutamine: Purjeriie, present
- Siid. Riie, trikoo, niit
- Vill. Riie, trikoo ..

Tehiskiud:

- Klaaskiudained. Kasutamine Kõisikud, korrutatud niit, pael, riie, armeeriv materjal
klaasplastides

Sünteesilised kiudained:

- Polüamiid. Sünt. Kiudained, sünt. Paber, kile, liimid, lakid, antifriktsioontooted
- Polüamiid kiudained. Kangad: kapron (NL), nailon, kevlar, tolvar (USA), perlon, aramiid
(SFV), dederon (SDV) ...
- Polüester. Lakid, kiled, klaasplastide sideaine
- Polüesterkiudained. Kangad: krimpeleni ja melaani tüüpi materjalid, lavsaan (NL), terileen
(Suurbrit), dakroon (USA), elaan(Poola)...

Plastehituskonstruktsioonid, eriti kangas- konstruktsioonid

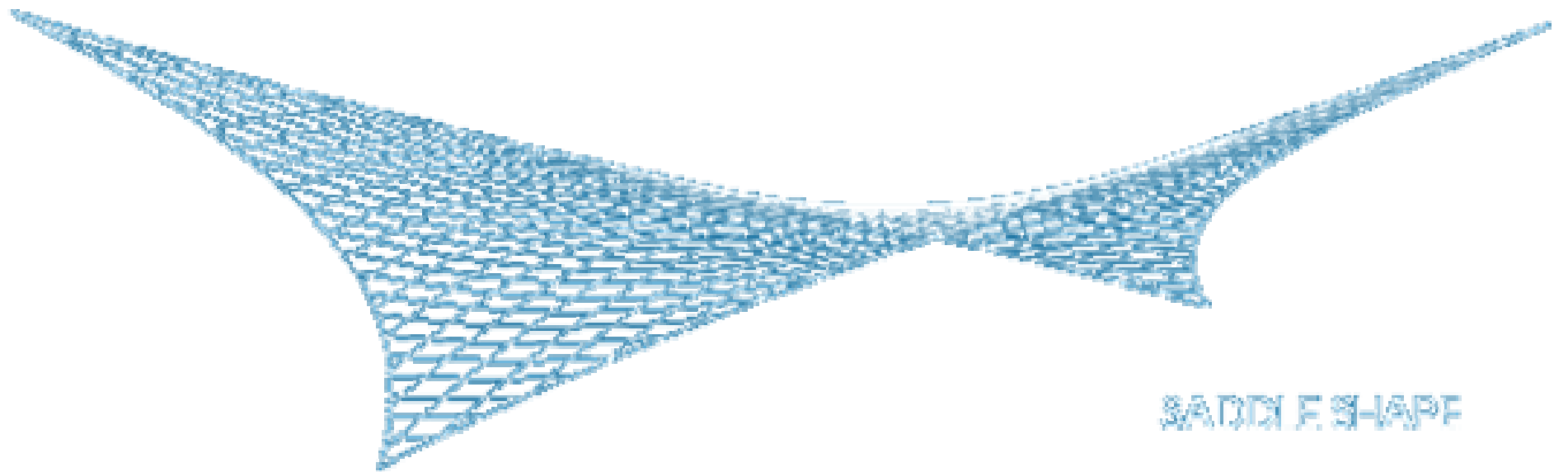
- Polüpropüleen. Kasutusala: Kiudained, kiled (Agressiivsetele vedelikele vastupidav)
- Polüpropüleenikiudained. Uppumatud köied, võrgud, filtri ja kattematerjalid
- Polüuretaankiudained. Riietusesemed, lükra (USA), neolaan (Jaapan)...
- Polüetüleen agr. Termoplastsed kiled, mahutid, vedelikele vastupidav
- Polüvinüülkloriid. Vinüülplast, jne.

Enamlevinud telkkangaste kattematerjalid: PVC, Teflon (TFET, polütetrafluoretüleen)

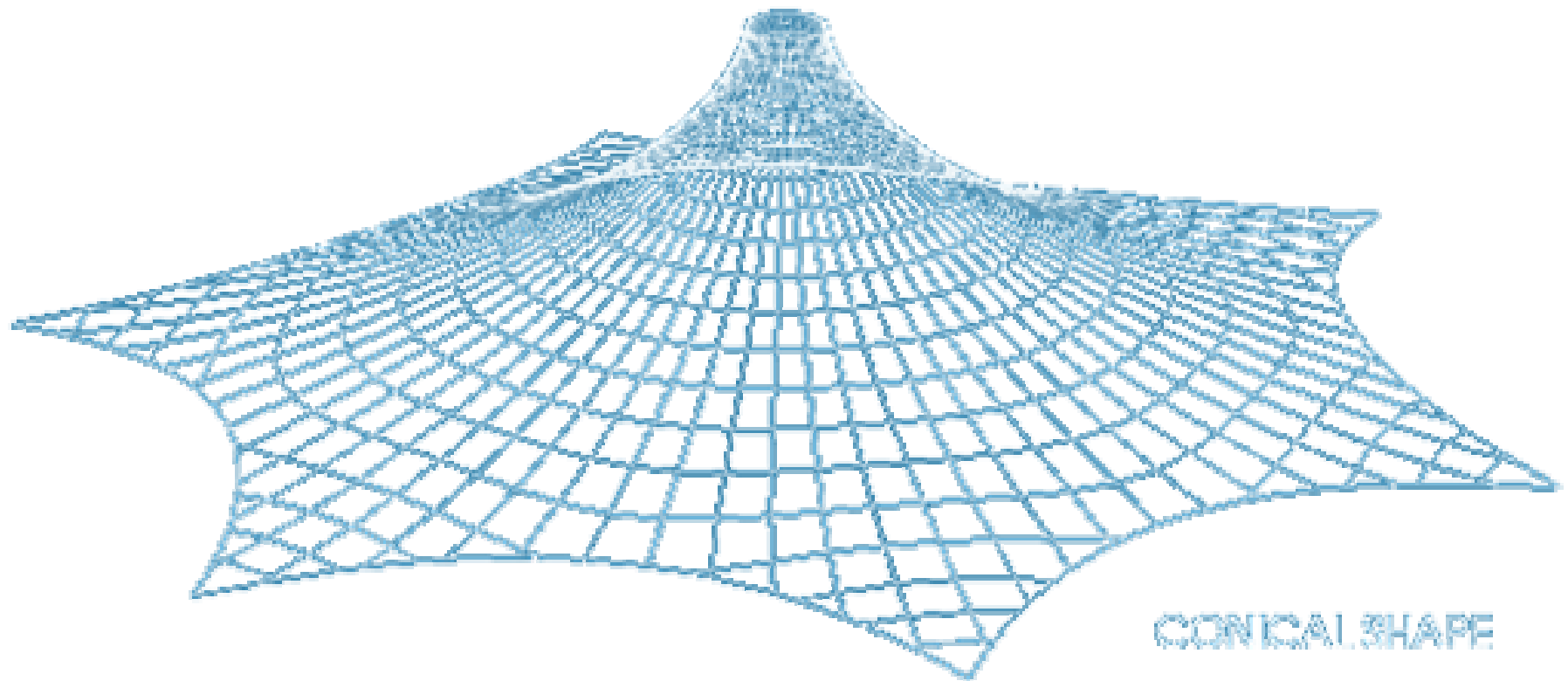


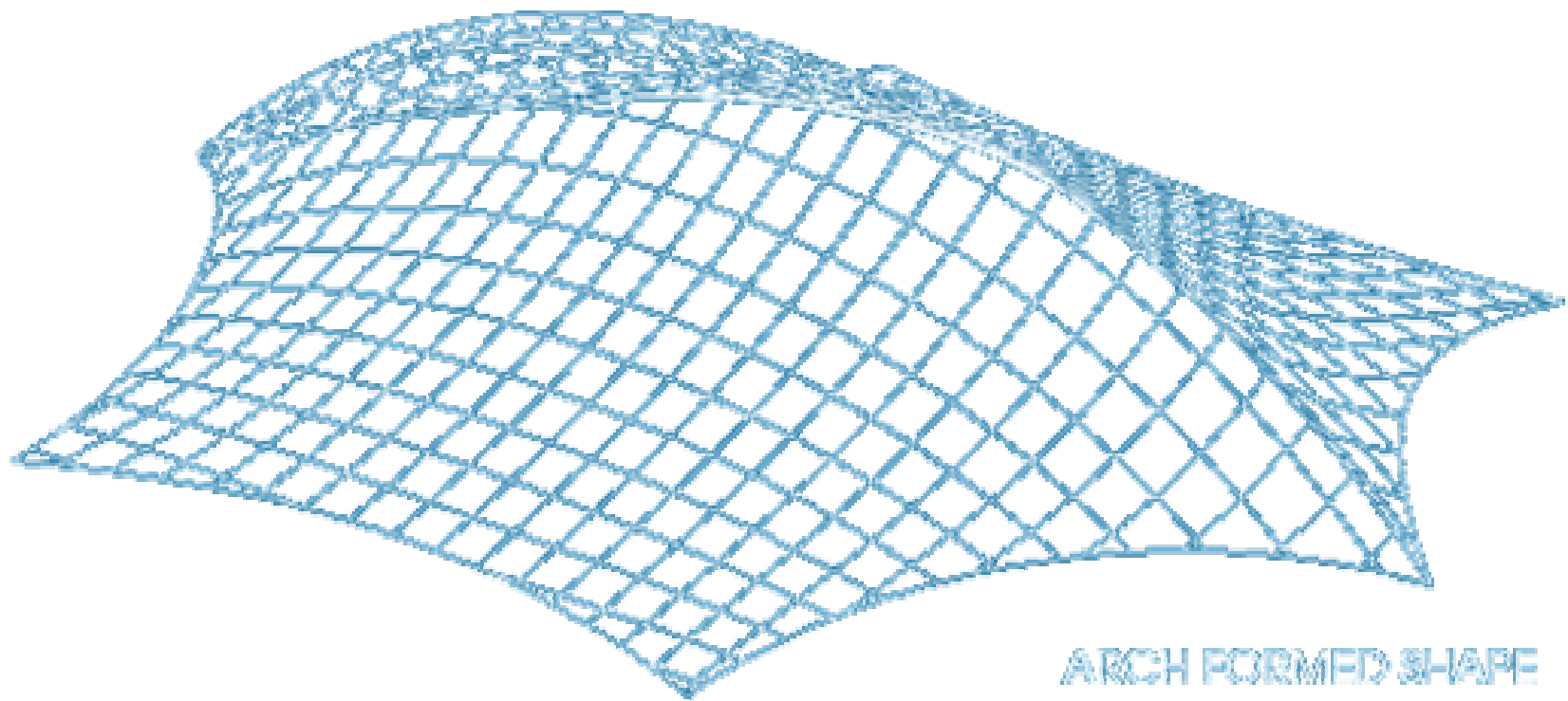




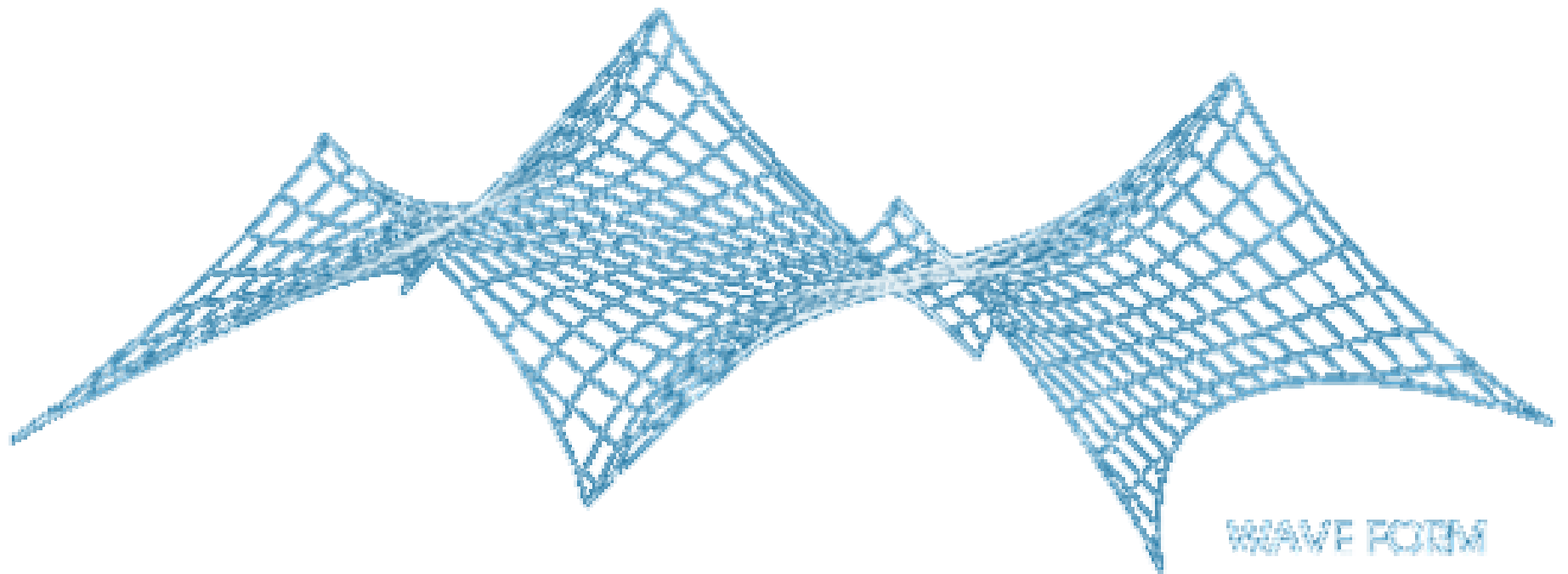


SADDLE SHAPE

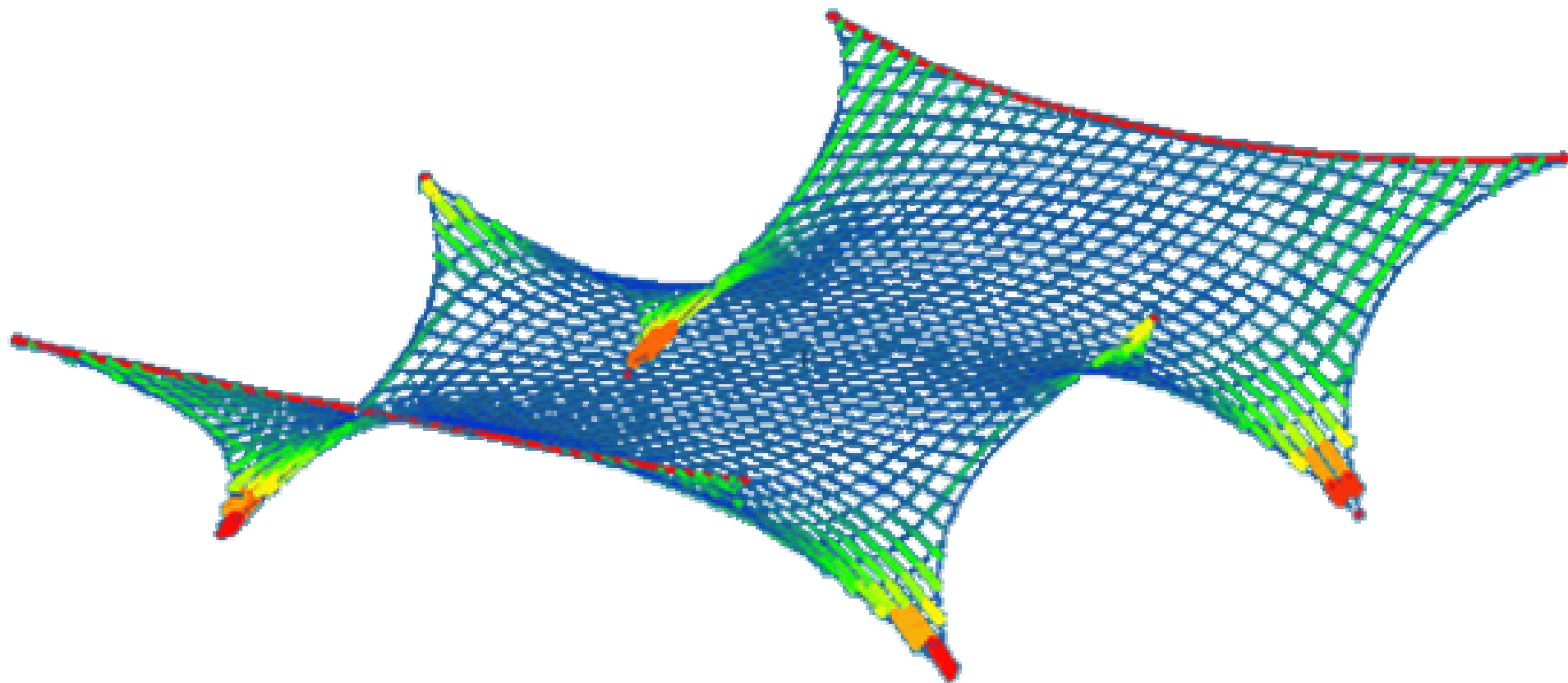


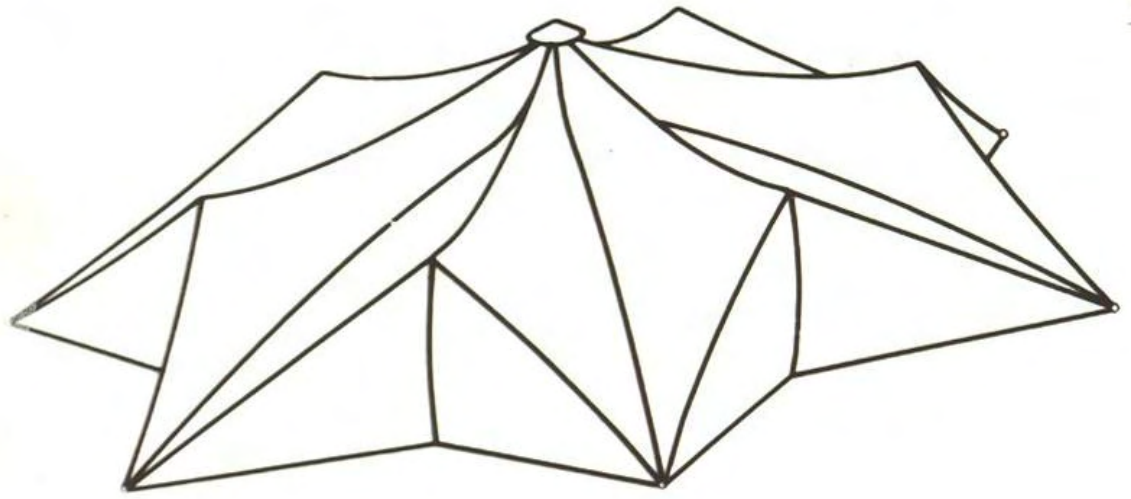
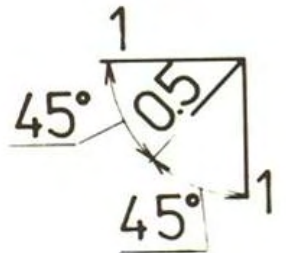
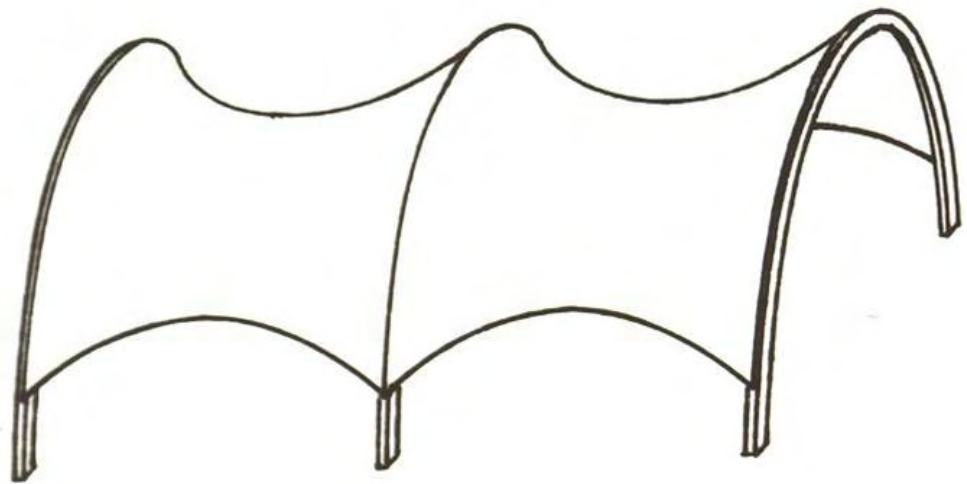


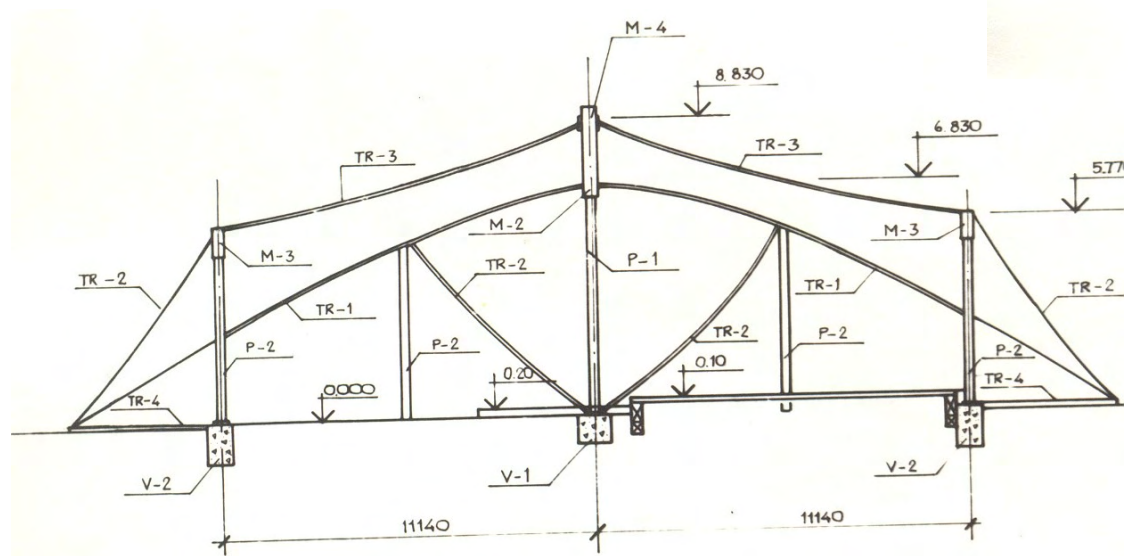
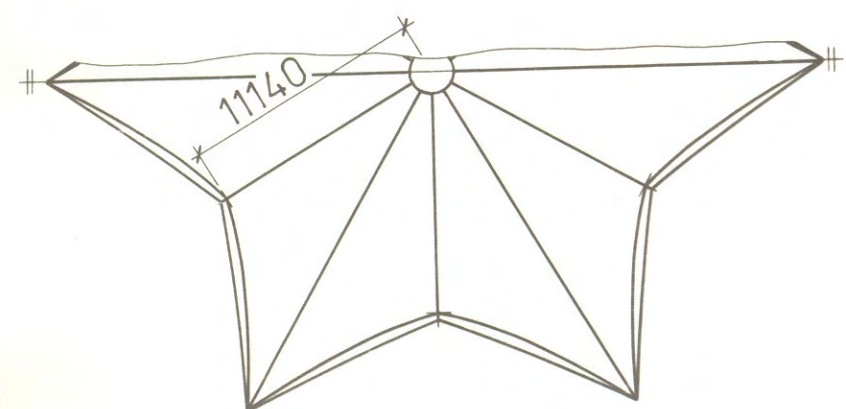
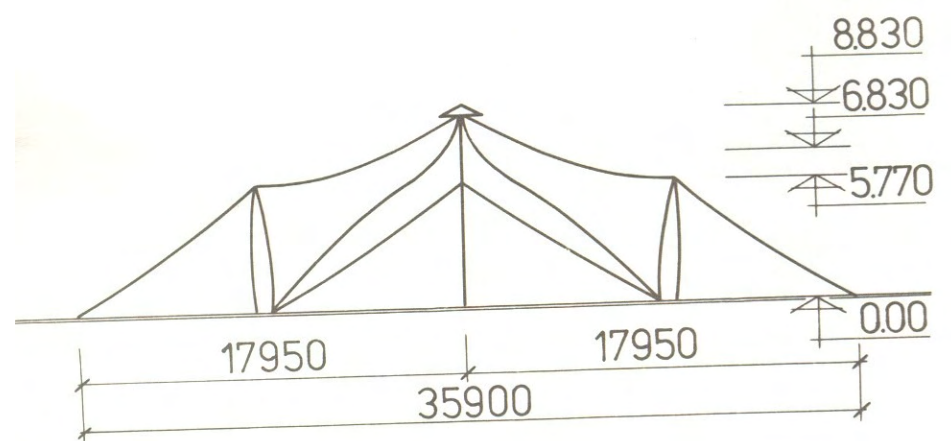
ARCH FORMED SHAPE

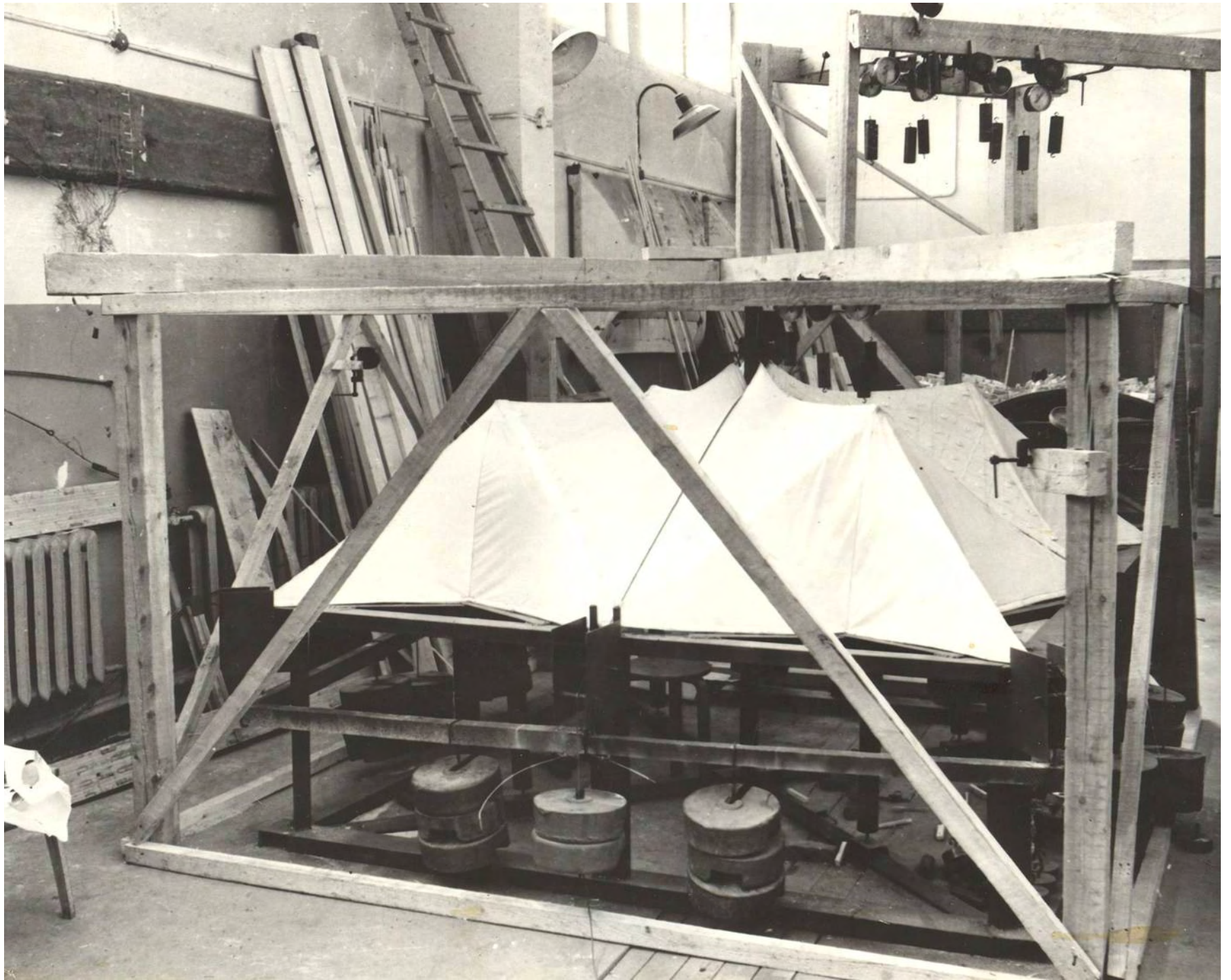


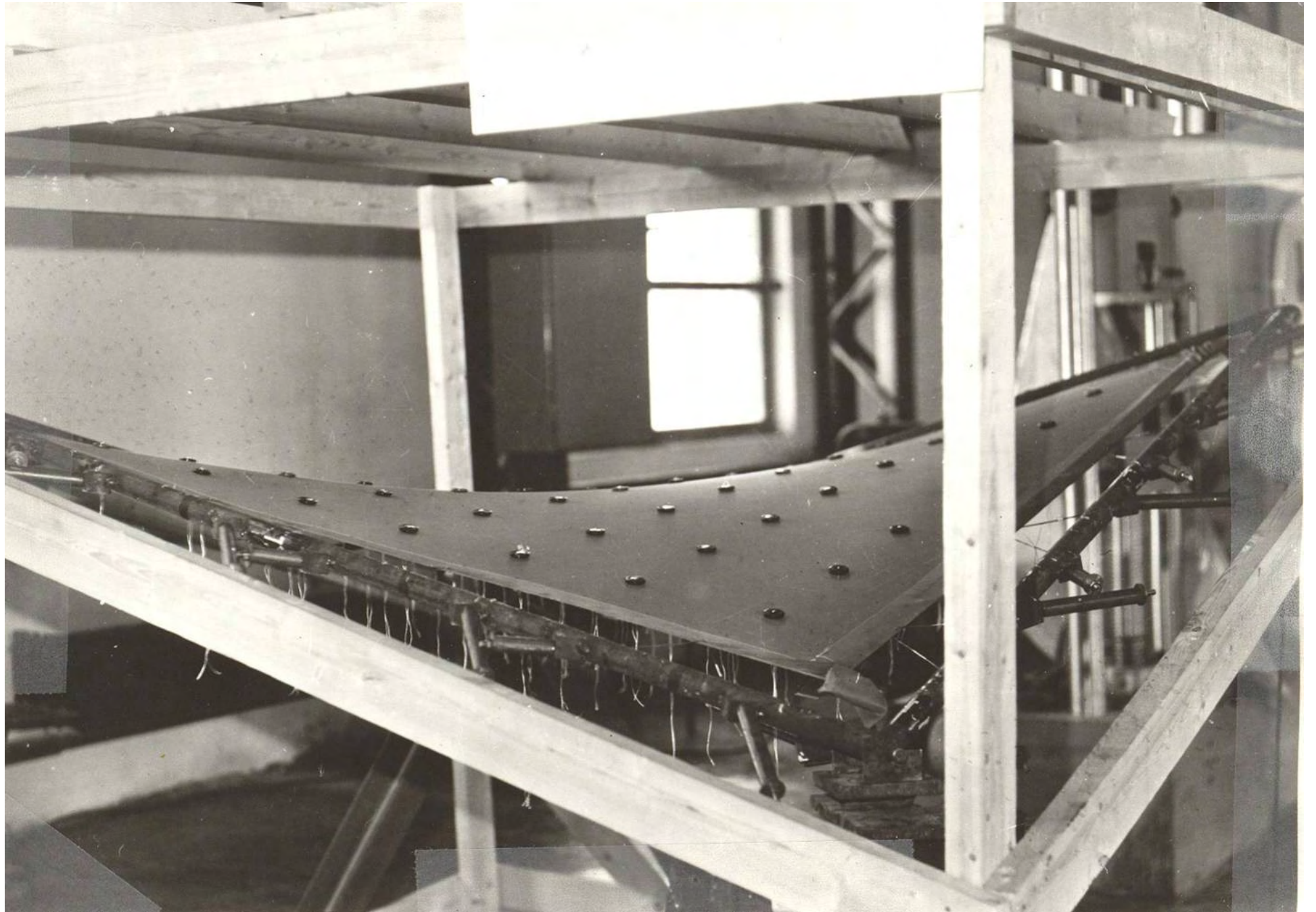
WAVE FORM

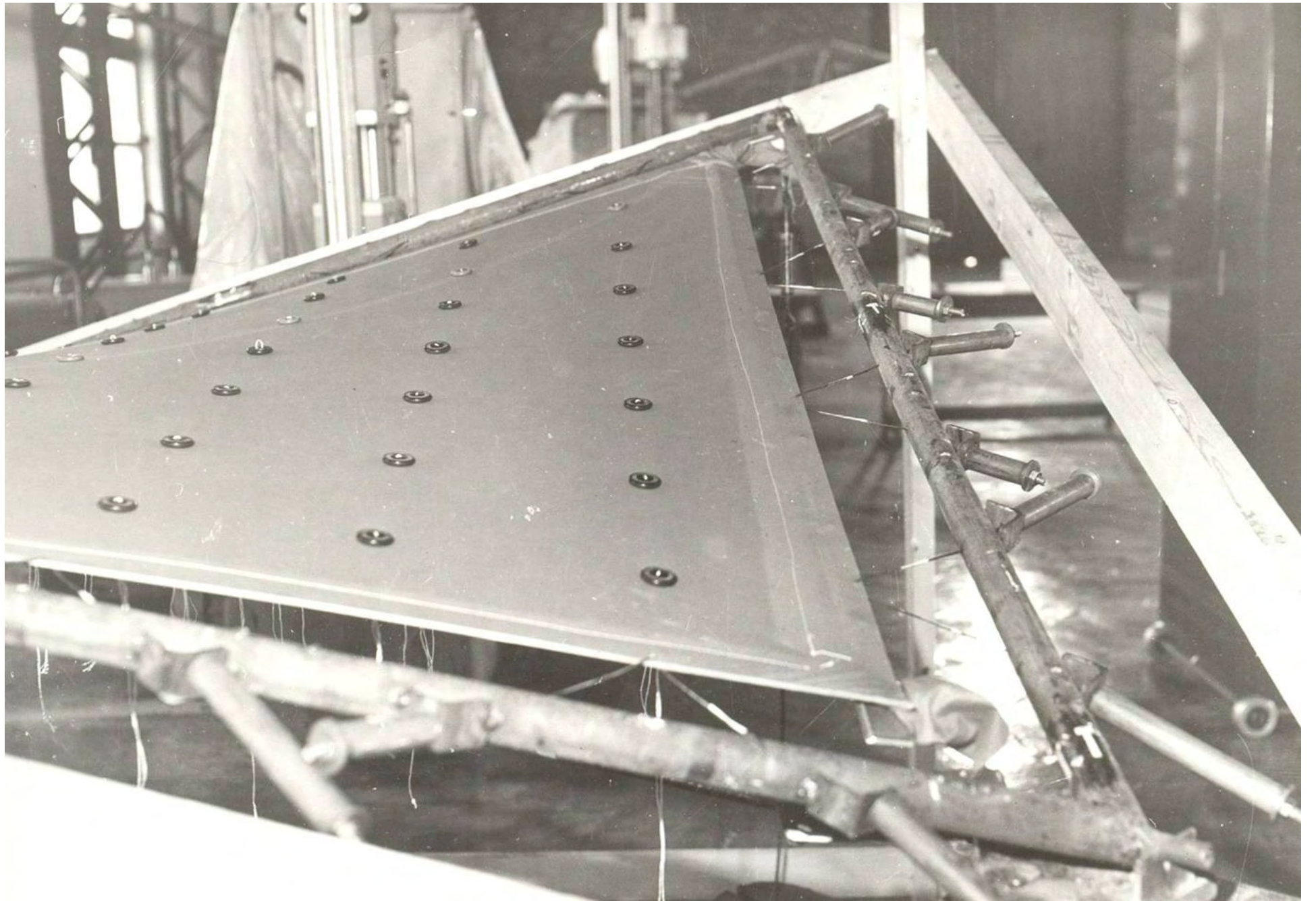


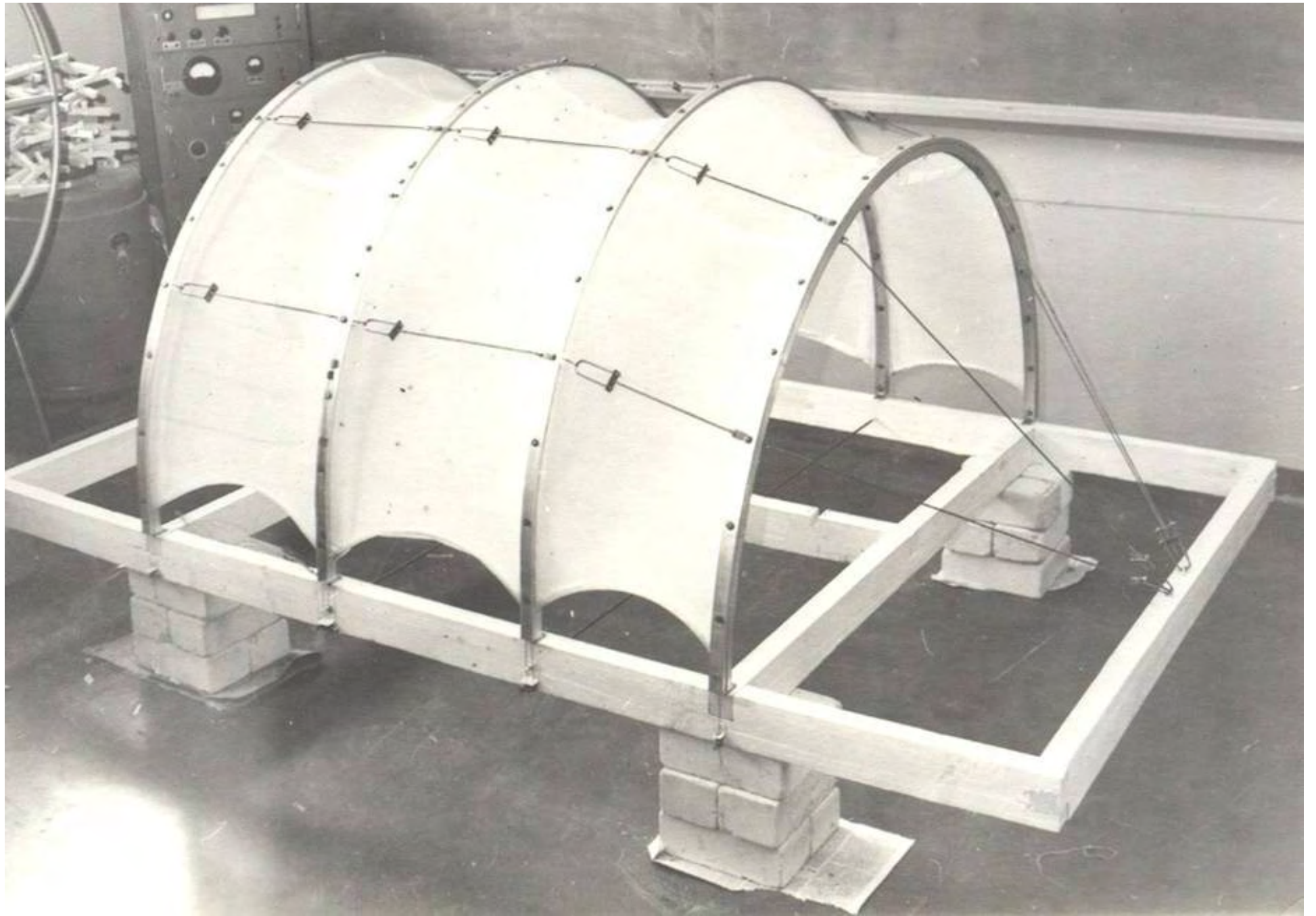


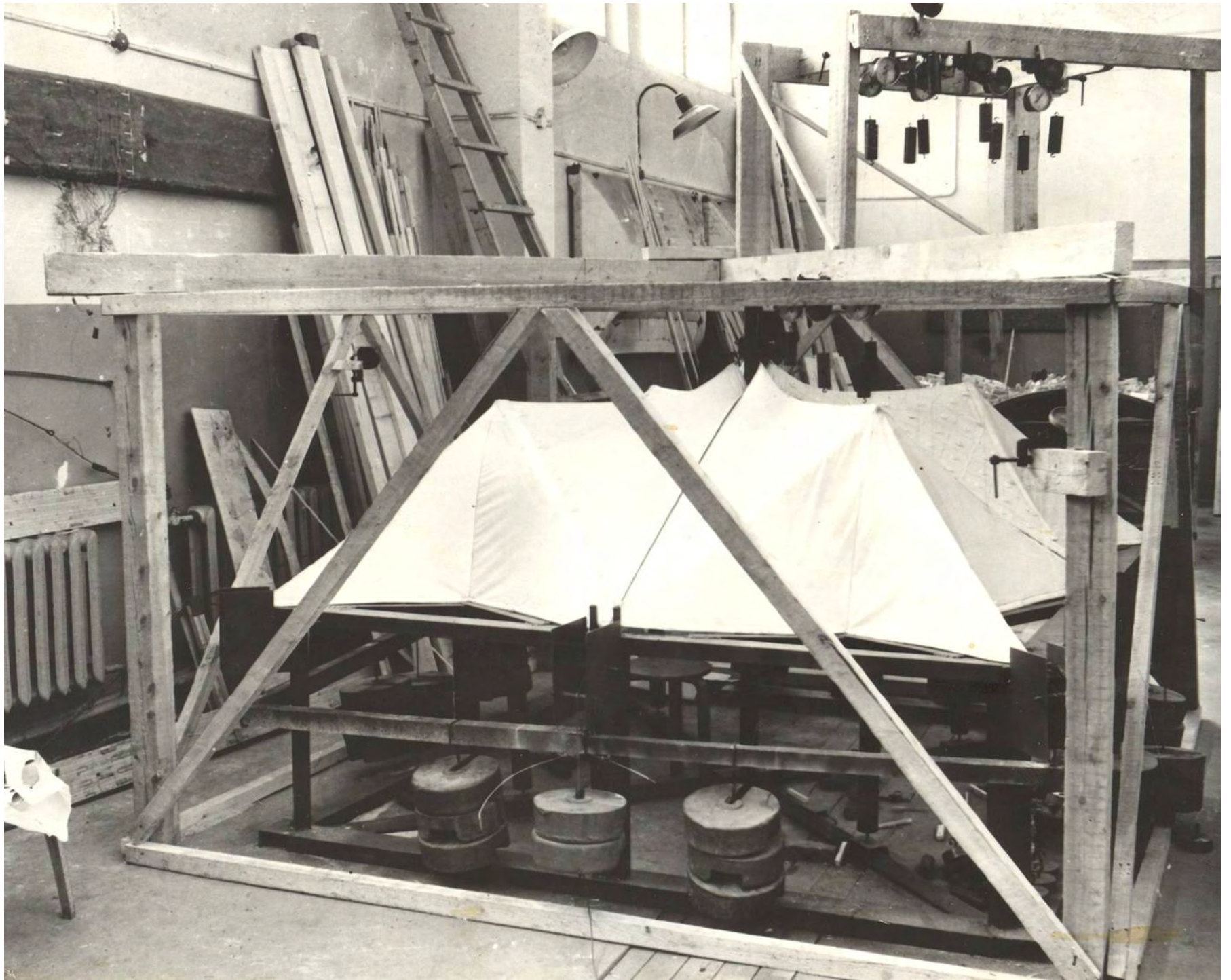




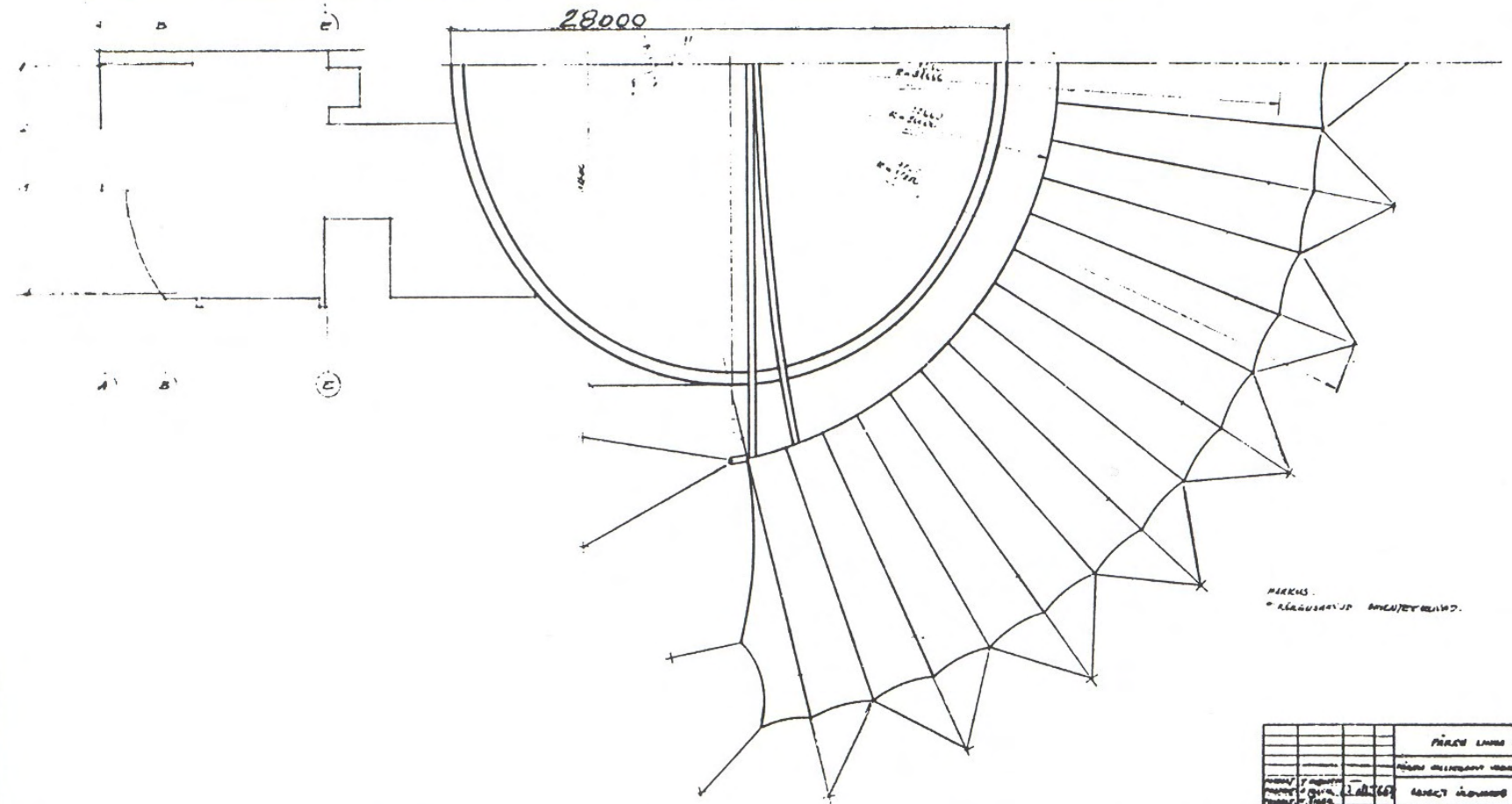
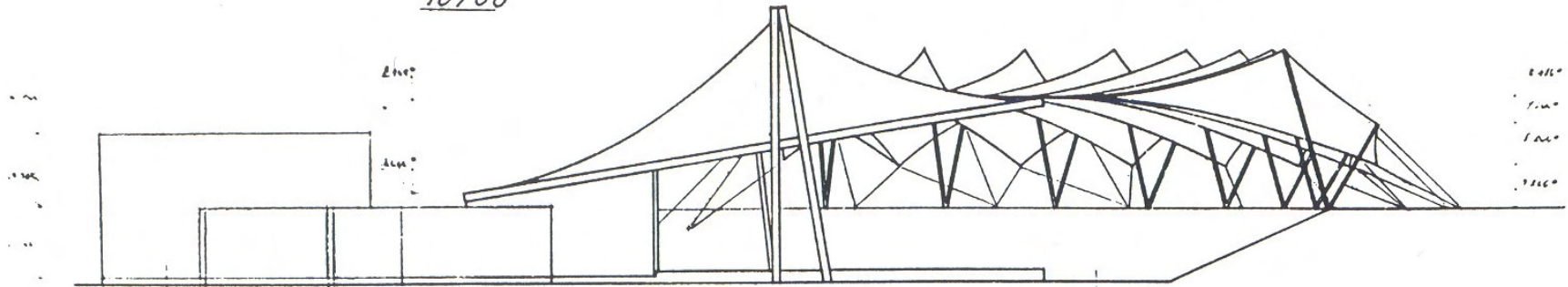






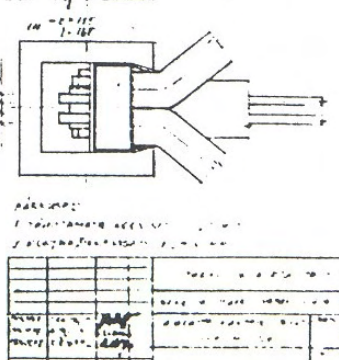
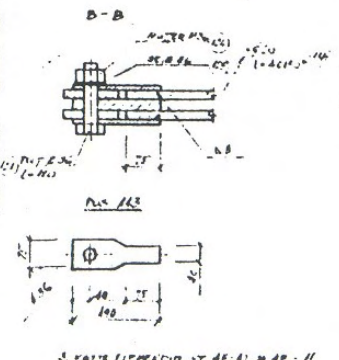
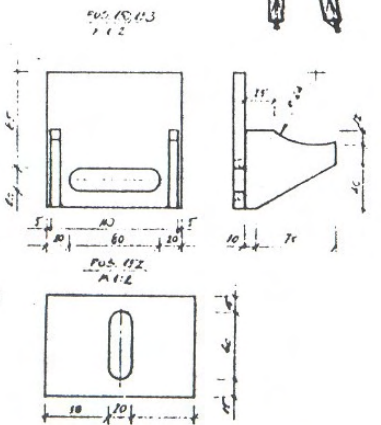
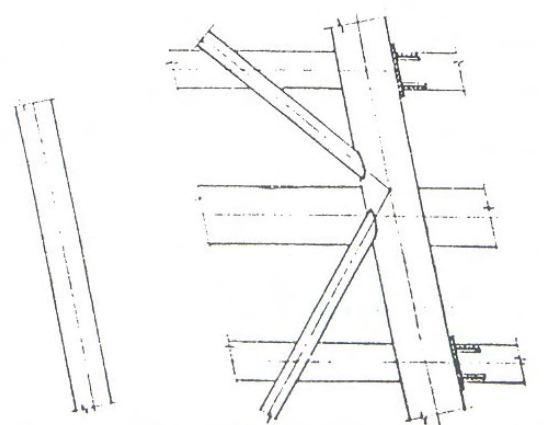
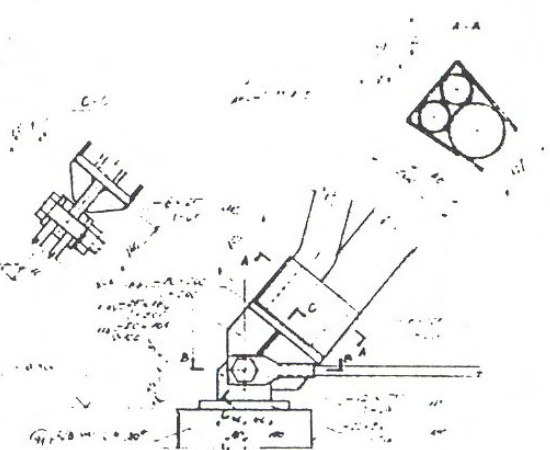
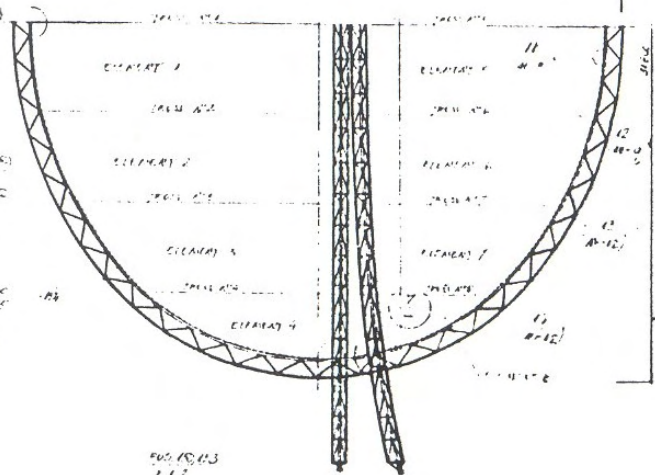
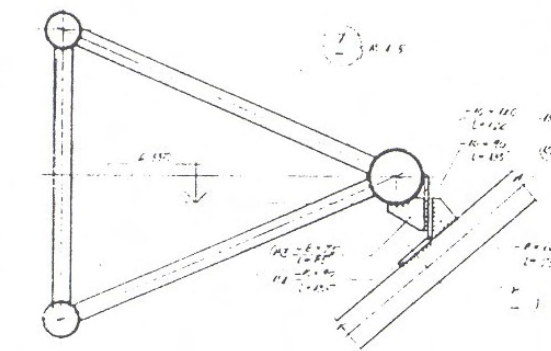
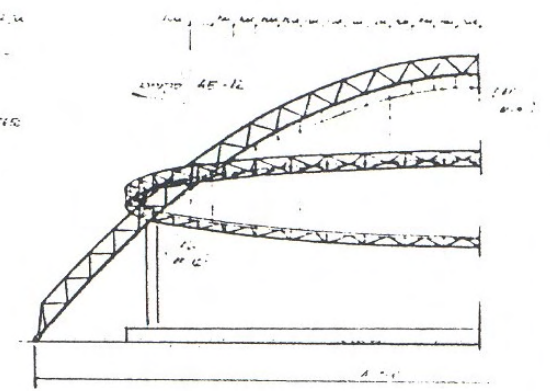
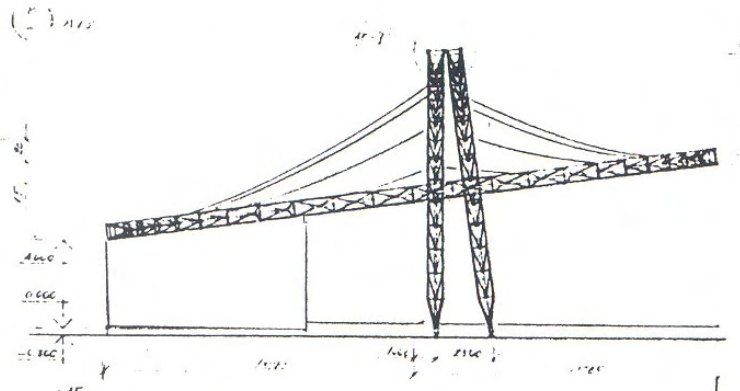
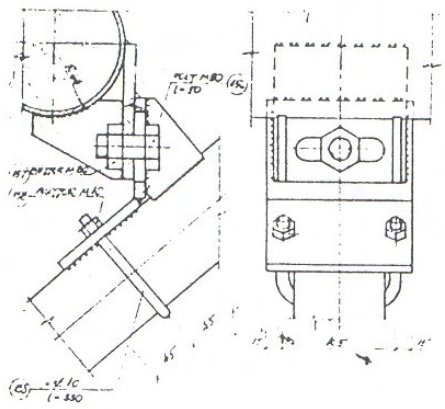


10700



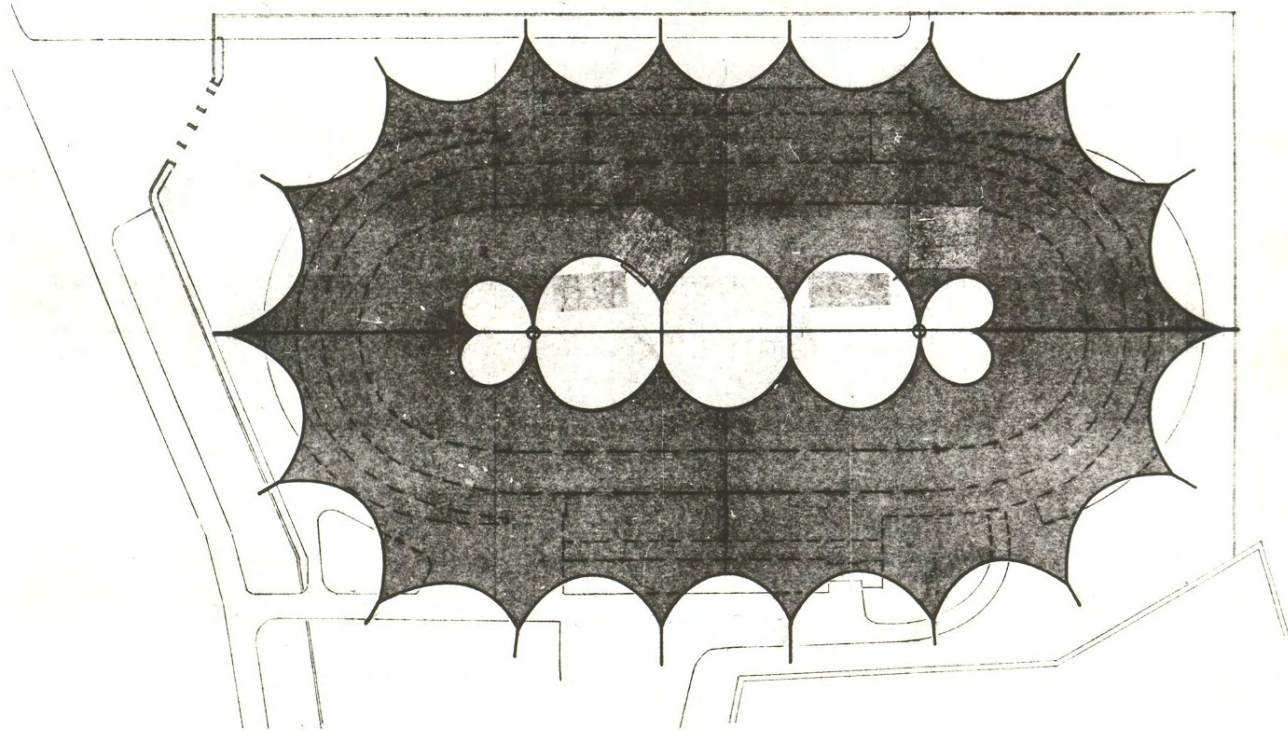
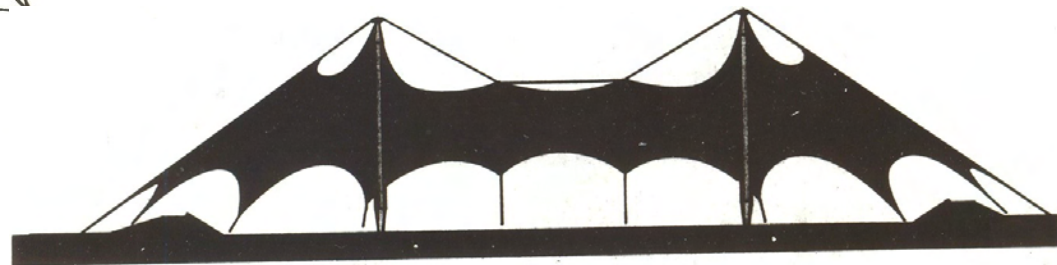
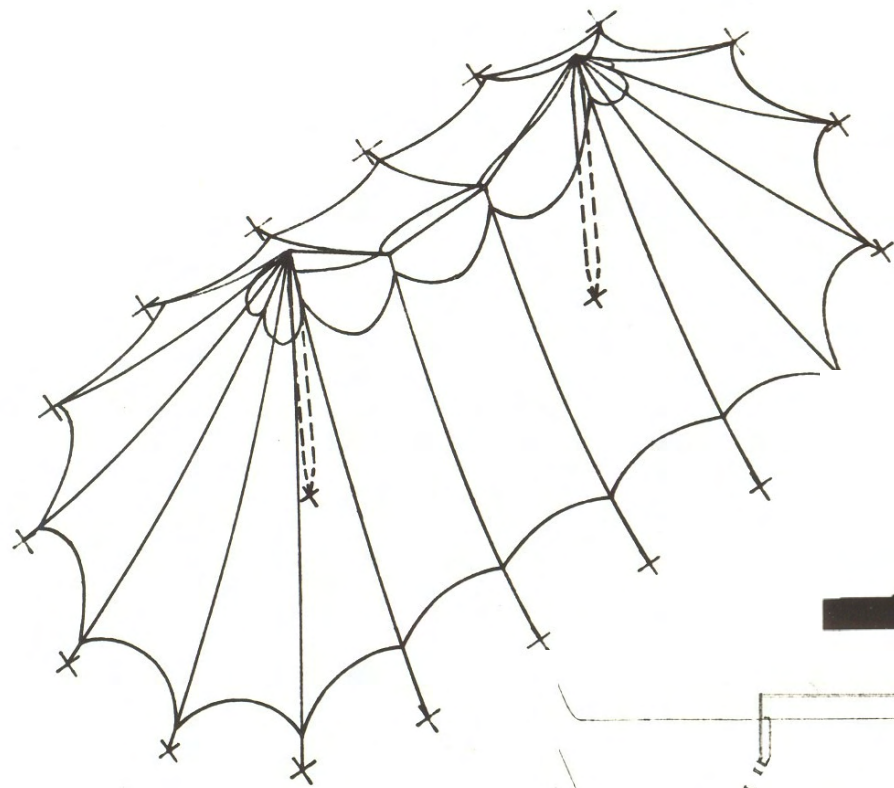
MARKAS:
 "ALGAMINIS" AP BONEJUT' BILIND.

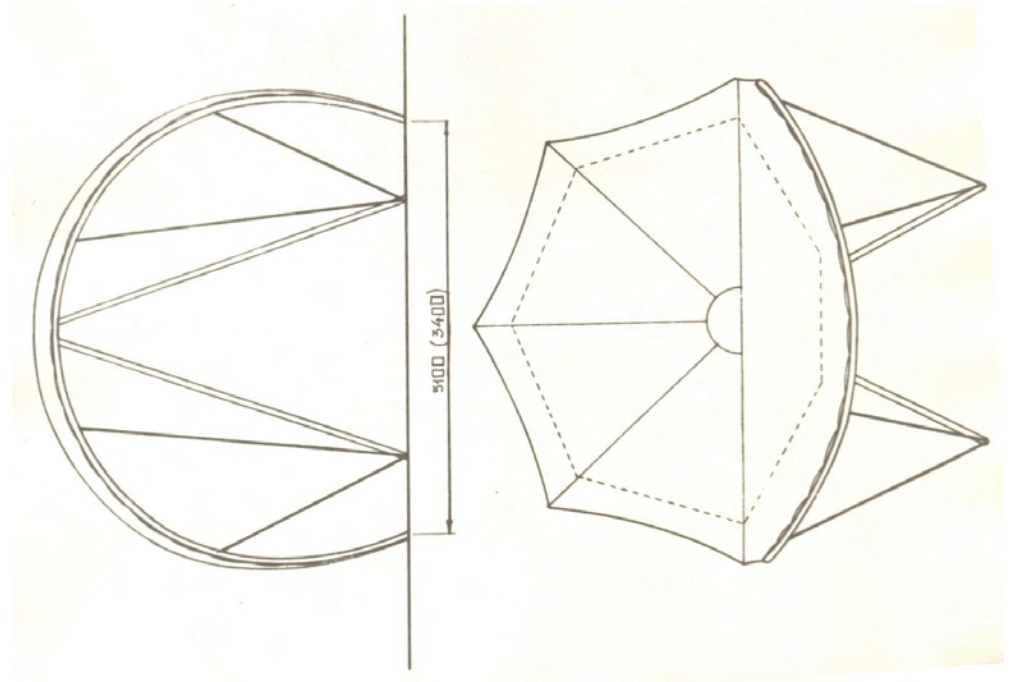
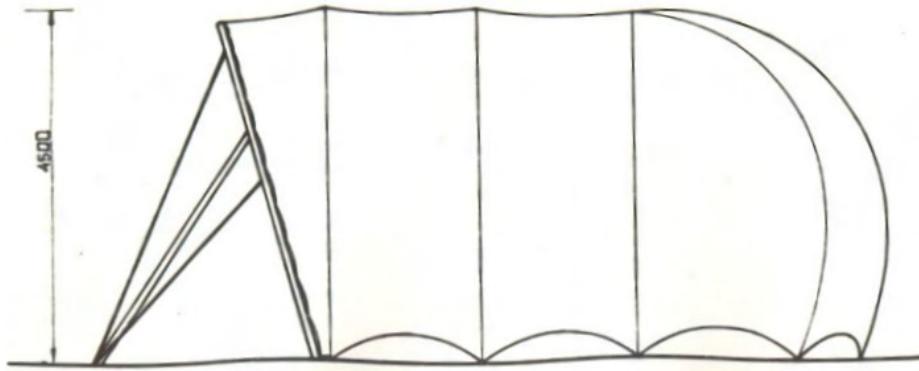
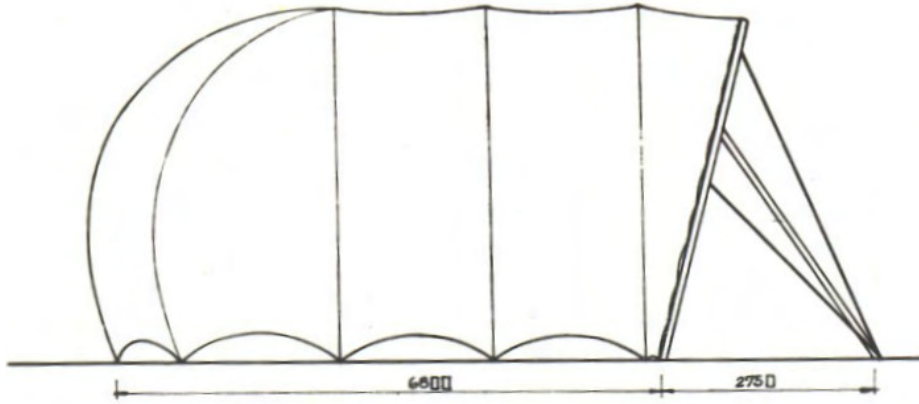
PĀRĀDĒ LĪMĀS ALI TĪRĪTĀKUMIEM	
PĀRĀDĒ ALI TĪRĪTĀKUMIEM VEIKĀMĀJĀS BĒGĀMĀS	
PROJEKTA VEIKĀMĀJĀS BĒGĀMĀS	ALGAMINIS
PROJEKTA VEIKĀMĀJĀS BĒGĀMĀS	ALGAMINIS



№	ИЗМЕНЕНИЯ	ПОДПИСАНИЕ	ДАТА
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			



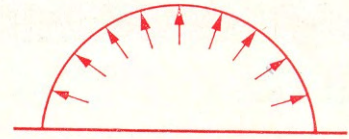
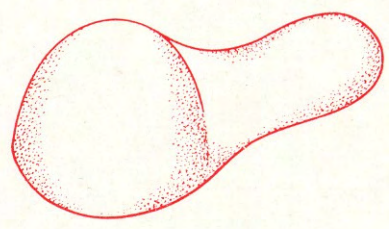
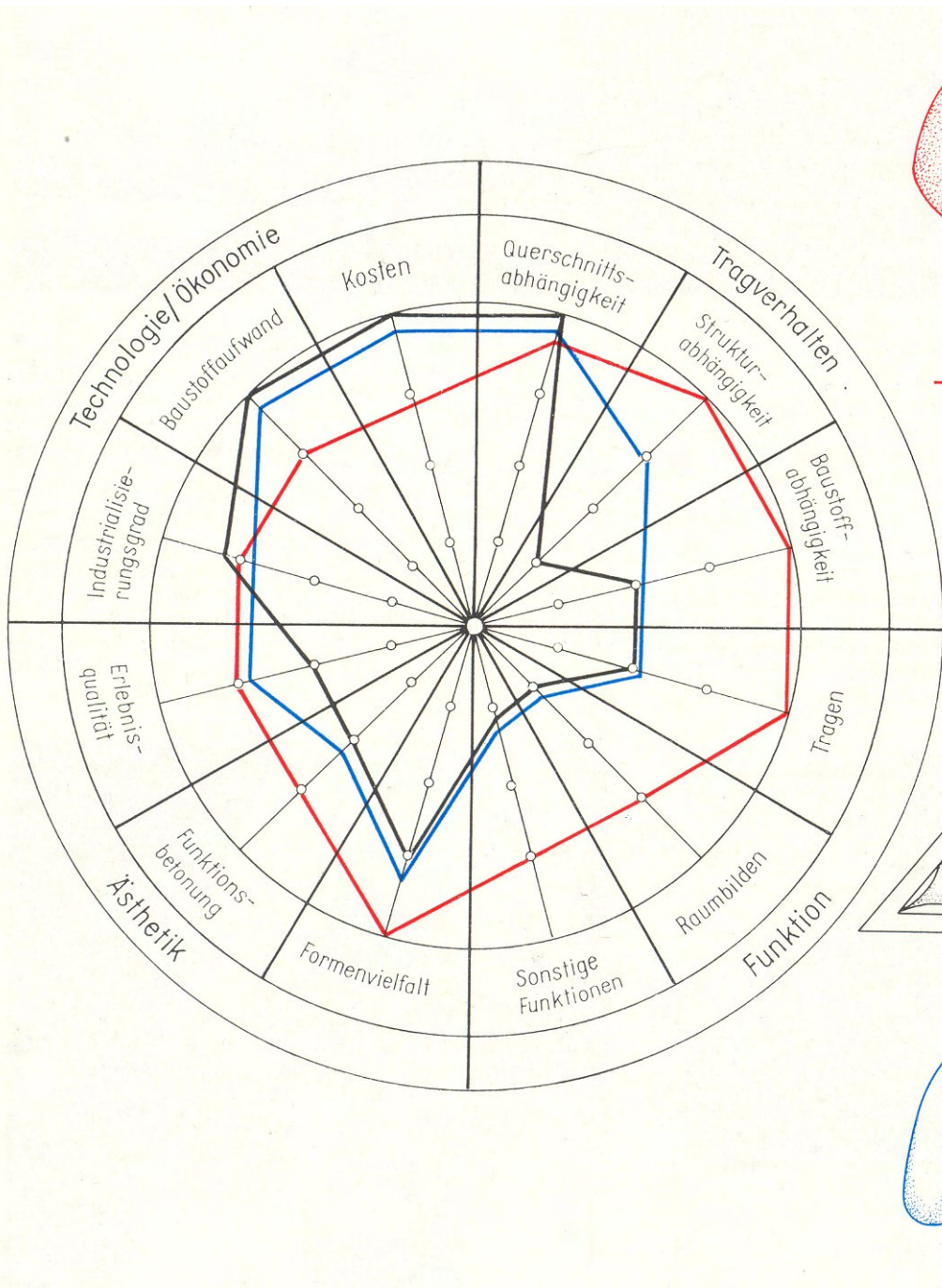




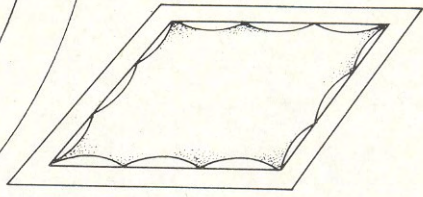




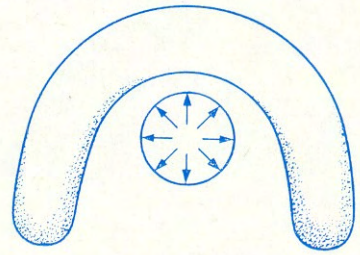




Traglufthallen



Pneukissen



Schläuche

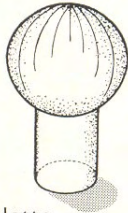
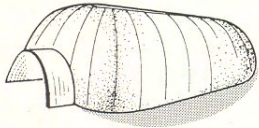
Formbeispiele:

Einsatzmöglichkeiten im Gesellschaftsbau und Industriebau
(mobil oder stationär):



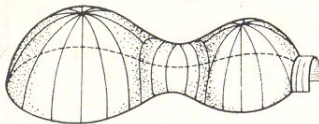
Halbzylinder mit:
– Endviertelkugeln oder
– Endvierteloktaedern

- Ausstellungshallen
- Markthallen
- Kinos
- Sporthallen für Wassersport, Reiten oder Leichtathletik
- Gaststätten
- Lagerbauten
- Winterbauhallen
- Produktionshallen



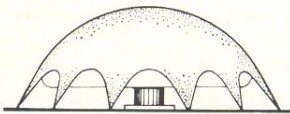
Kugelkalotte

mobile Schutzhüllen, z. B. für Plattformen im Gleitbau
stationäre Schutzhüllen, Radarschutz (Radomkuppeln)



Kuppelausschnitte mit
eingefügtem Sattel

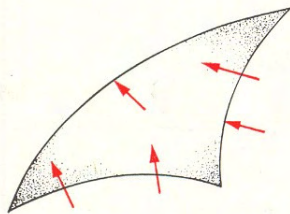
mobile oder stationäre Ausstellungshallen oder Lagerhallen



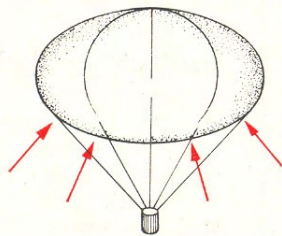
Translationsparaboloid

stationäre Ausstellungshallen über erdgeschößfreier Zone

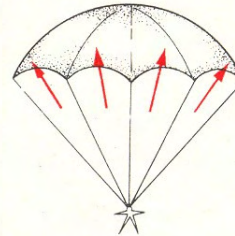
pneumatisch belastete Tragwerke



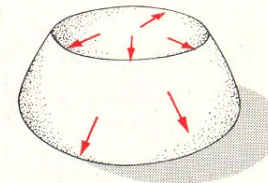
Segel



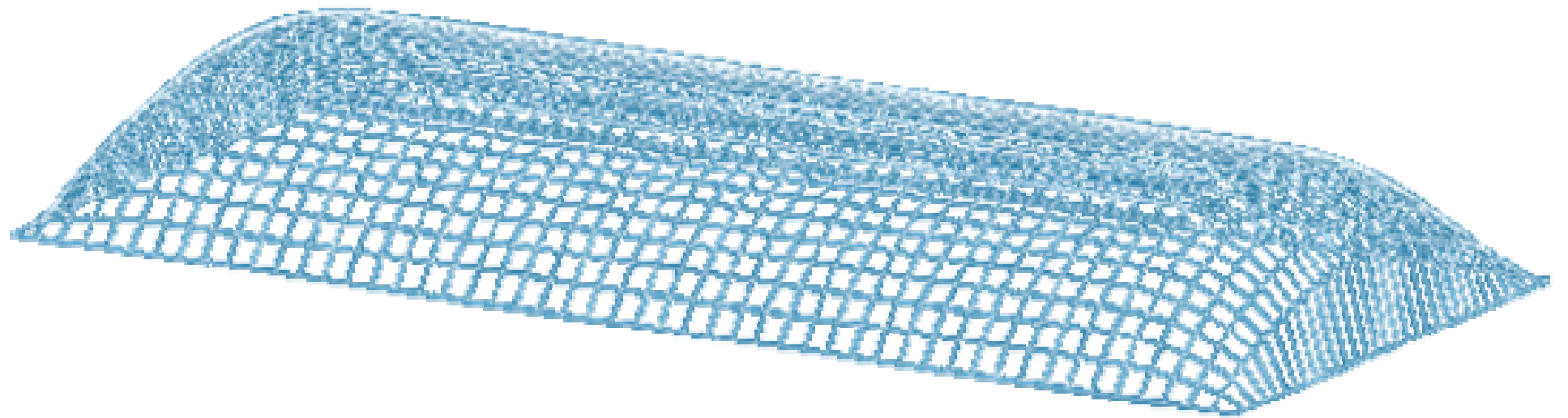
Ballon



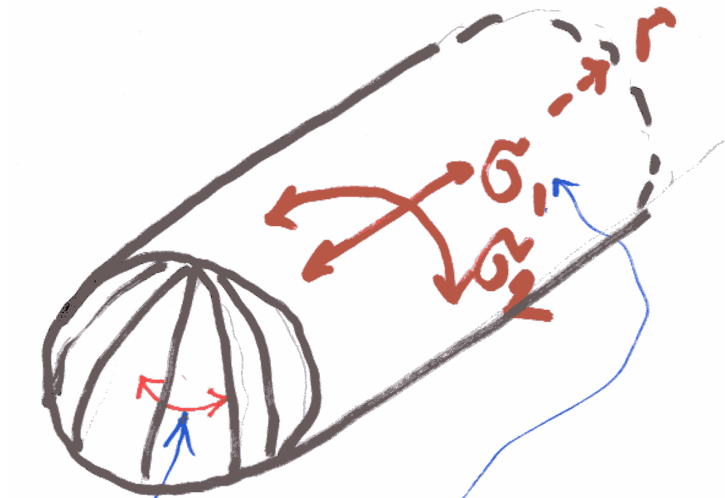
Fallschirm



Behälter



PNEUMATIC STRUCTURE



$f_{hoimi, d}$, kN/m
 $f_{nude, d}$, kN/m

$\sigma > 0$, välttämäksi
 puumateriaalin
 taivuttamista

Ylipaine

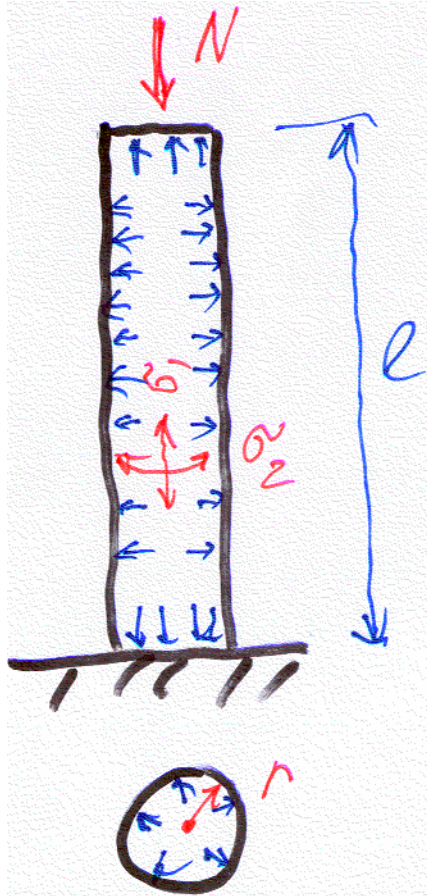
$$\sigma_1 = (p + q - w) \frac{r}{2} \leq f_{t,d} ; f_{k,d}$$

$$p \geq q_{tuuli}(w)$$

$$p \geq q_{lumi}$$

$$\sigma_1 = (p + q - w) r \leq f_{t,d} ; f_{k,d}$$

$$\sigma_2 = (p + q - w + p_{lumi}) \leq f_{t,d} ; f_{k,d}$$



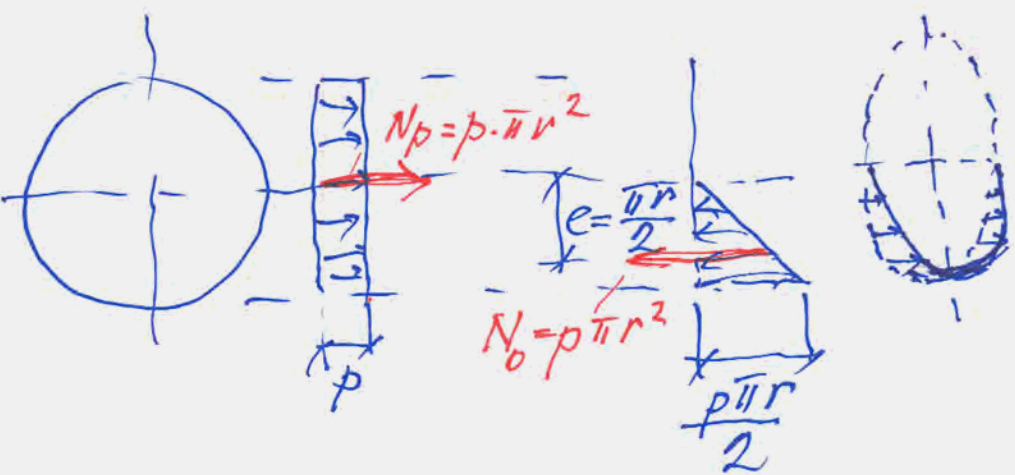
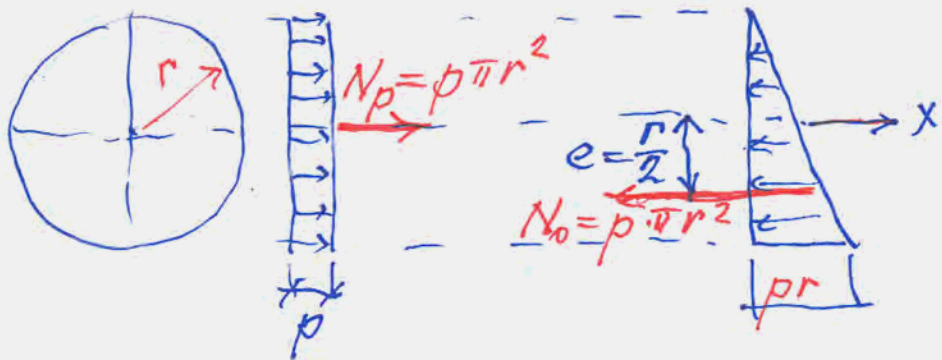
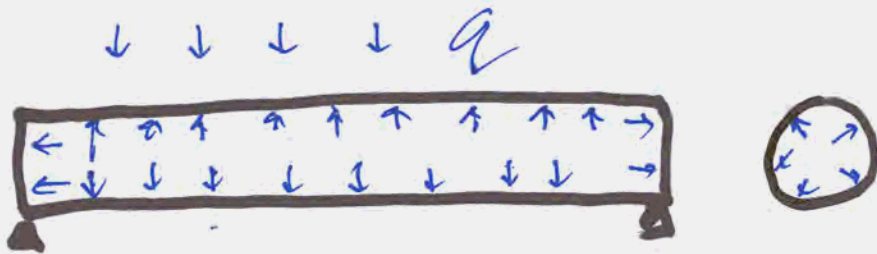
$$\sigma_1 = \frac{p \cdot r}{2} \leq f_{l,d}; f_{k,d}$$

$$\sigma_2 = p \cdot r \leq f_{l,d}; f_{k,d}$$

Вакавум $N \leq p \cdot \pi \cdot r^2 \cdot \psi$

$$\lambda = l/r$$

λ	p, MPa			
	0,1	-	-	0,3
20	ψ			
	0,85	-	-	0,3
60	0,12	-	-	0,06



1) Rajatila alka kuoren taittamisesta (puristus)

$$N_p = p \bar{u} \cdot r^2$$

$$\Sigma X = 0: N_p = N_0$$

Taittamisen rajatilaa

$$M_{tr} = N_p \cdot e = \frac{p \cdot \pi r^3}{2}$$

$$M_q \leq \frac{p \cdot \pi r^3}{2}$$

2) Vakavuuden (yleisen pysyvyyden) ehto:

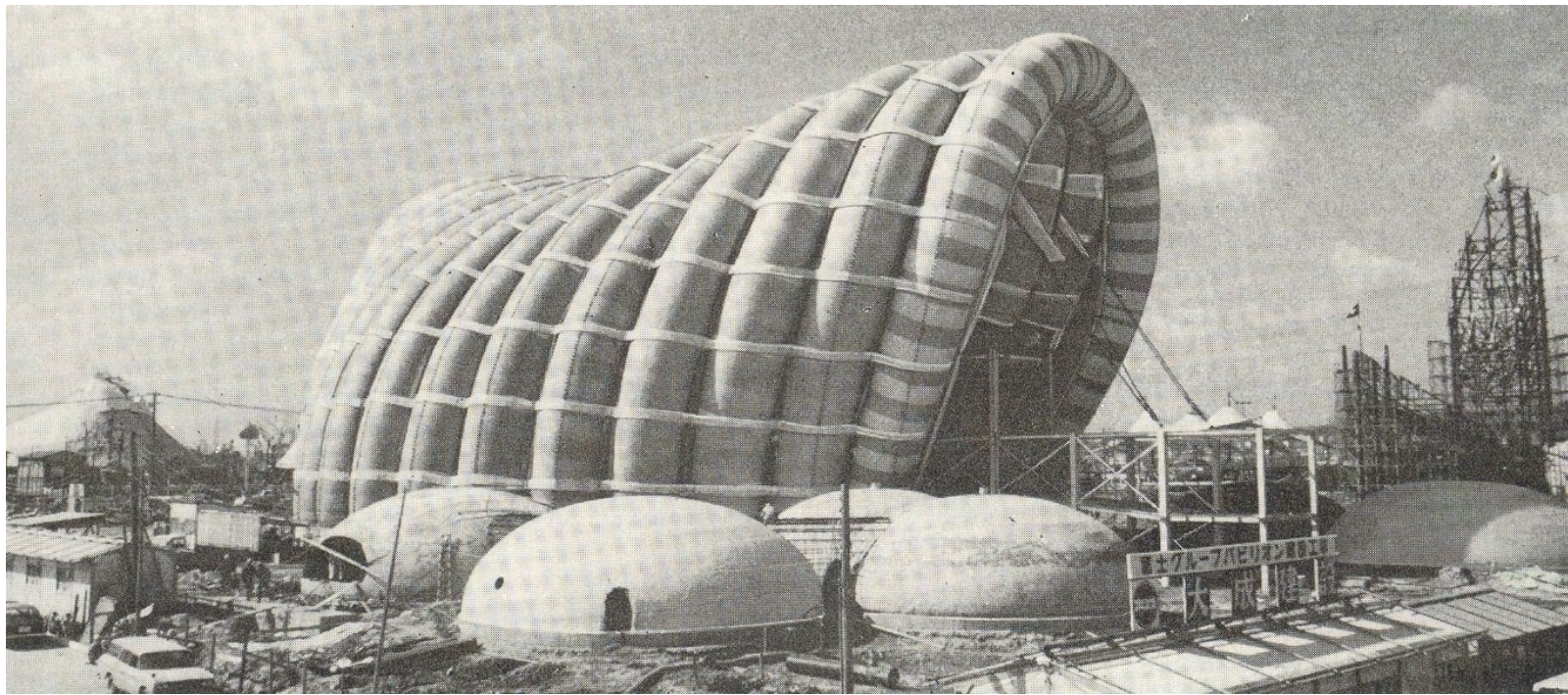
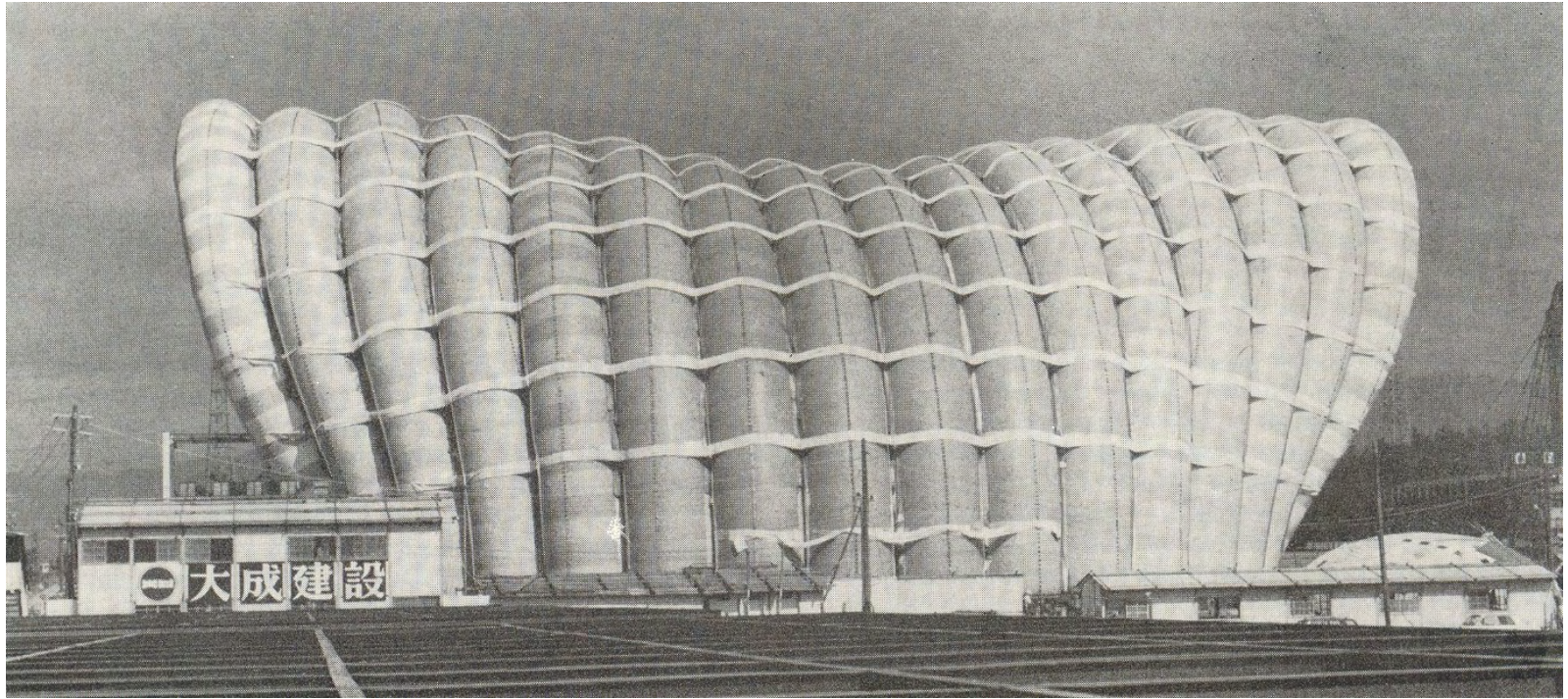
$$\sigma_{max} = \frac{p \cdot \pi r}{2}$$

Rajatila momentti (sisävoimien momentti)

$$M_r = N_p \cdot e = \frac{p \cdot \pi^2 \cdot r^3}{4}$$

Pysyvyyden ehto

$$M_q \leq \frac{p \cdot \pi^2 \cdot r^3}{4}$$



Täna tähelepanu eest!