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# Does heat, air, moisture modelling really help in solving hygrothermal problems

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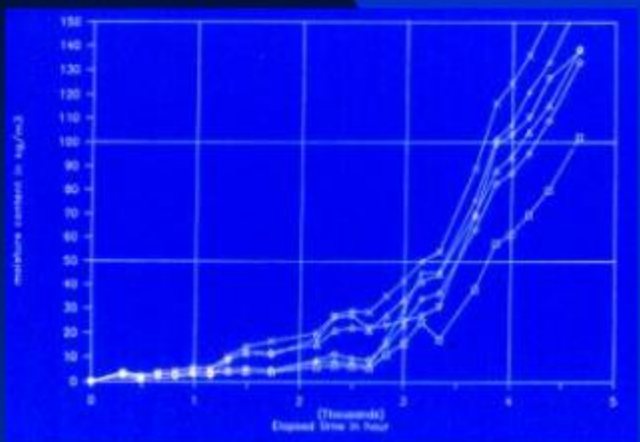


# Outline

- Introduction
- Combined HAM modeling
- Weaknesses in actual models
  - Materials composed of identical REV's?
  - Contact resistances?
  - Geometry?
  - Rain run-off?
  - Wind pressure induced moisture flow?
  - Gravity effects?
  - Airflow?
  - Not considering risk!
- Practice example
- Conclusions

# Combined HAM modelling

Conservation of heat, mass and momentum

$$\mathrm{div}\big(\text{Flux of X}\big) + \mathrm{S(X)} = -\frac{\partial X}{\partial t}$$

Flux equations: 2 types, diffusive and bulk

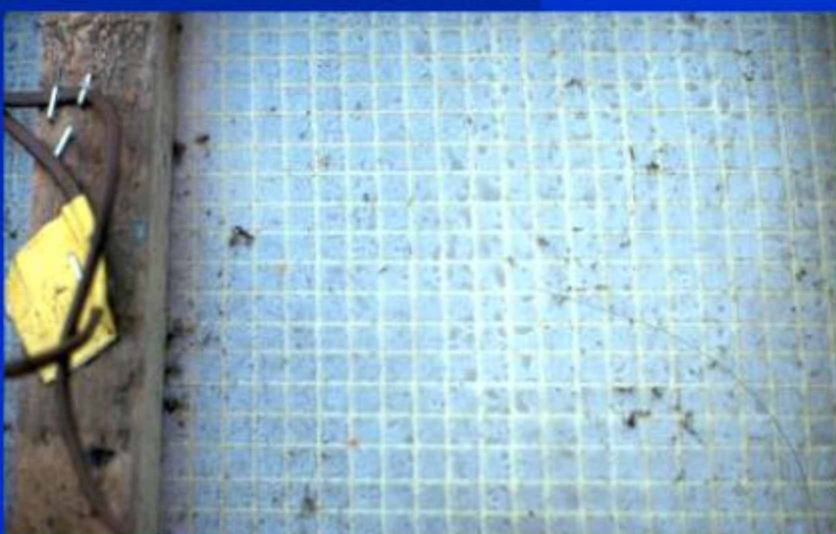
$$q = -\lambda \,\mathrm{grad}(\theta)$$
$$g_v = -\partial \,\mathrm{grad}(p)$$
$$g_w = -k_w \,\mathrm{grad}(s)$$
$$g_w = -k_{w,sat} \,\mathrm{grad}(P)$$
$$g_a = -k_a \,\mathrm{grad}(P_a)$$

↔

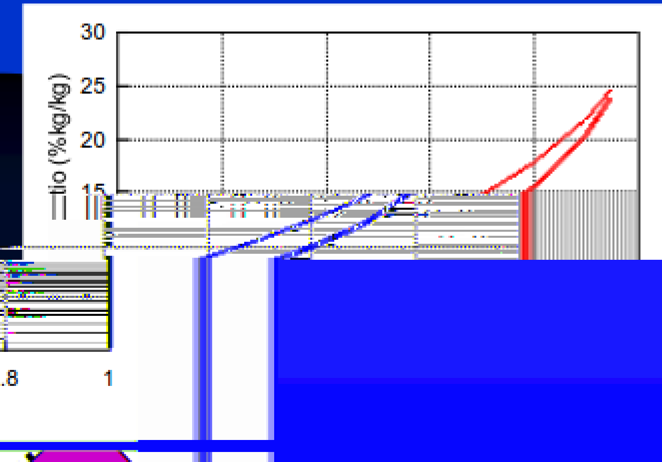
$$q = -mh$$
$$g_v = g_a x_v$$

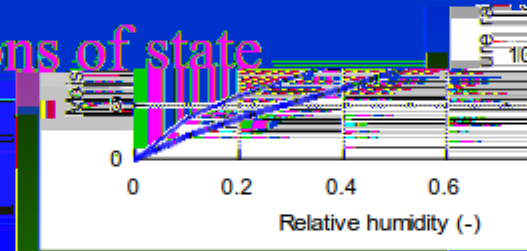
Storage (P: driving forces)

$$\frac{\partial X}{\partial t} = \sum C_i \frac{\partial P}{\partial t} \text{ with } C_i = \frac{\partial X}{\partial P}$$



# Combined HAM modelling



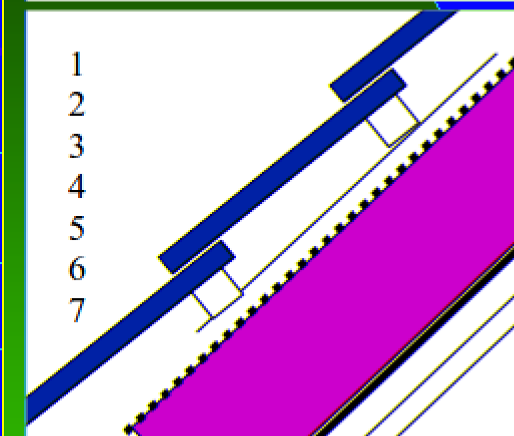

Equations of state

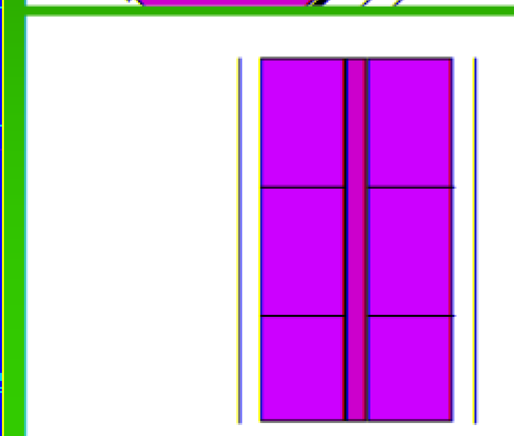
$p_{sat}=f(\theta, r_{eq})$

$h=c_p\theta+l_b$

Sorption isotherm

Geometry



Boundary, initial and contact conditions

Outside climate

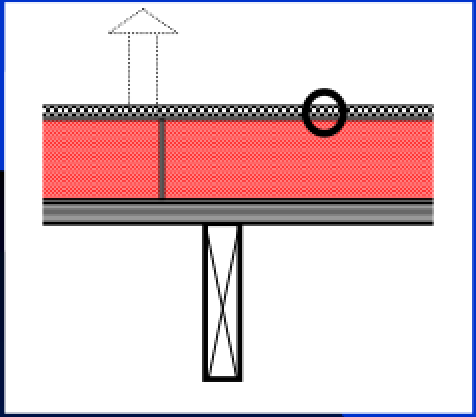
Inside temperatures

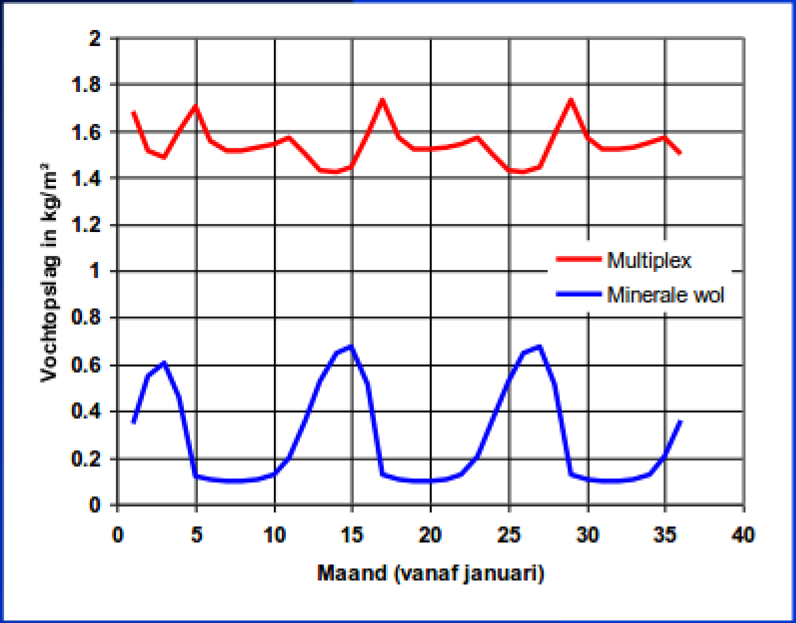
Inside relative humidity

Air pressure distribution

# Combined HAM modelling

## Mathematics






Materials assumed composed of equal REV's

In principle, equations work with average values per REV

For REV's infinitesimally small, a continuum approach applies

That results in PDE's with variable coefficients

Solved numerically

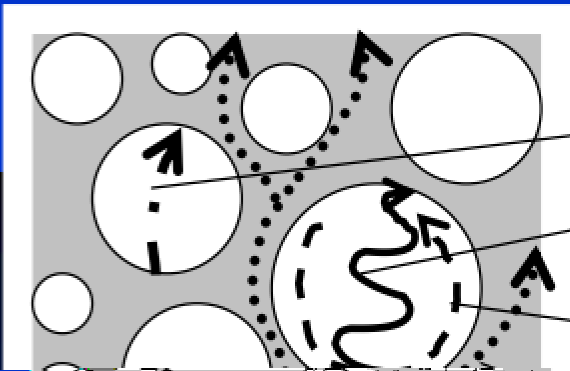
$$\rho c_p \frac{\partial \theta}{\partial t} = \nabla(\lambda \nabla \theta) + h_v \nabla(\delta_v \nabla p)$$

$$\rho \frac{\partial X}{\partial t} = \nabla(\delta_v \nabla p + k_w \nabla s)$$

# Combined HAM modelling

## Basic material properties

| | Storage | Transport |
|---|---|---|
| **General** | Density ($\rho$), porosity ($\Psi$) | |
| **Heat** | Specific heat capacity ($c_p$) | Thermal conductivity ($\lambda$) |
| **Air** | | Air permeability ($k_m$) or<br>Air permeance coefficient (a) and flow exponent (n) |
| **Moisture Vapor** | Specific moisture content ($\xi$) | Vapor permeability ($\delta_v$) or vapor resistance factor ($\mu$) |
| **Liquid** | | Moisture permeability ($k_m$) |



# Weaknesses in actual modelling

## Identical REV's?

general negative
aracteristics are
considered

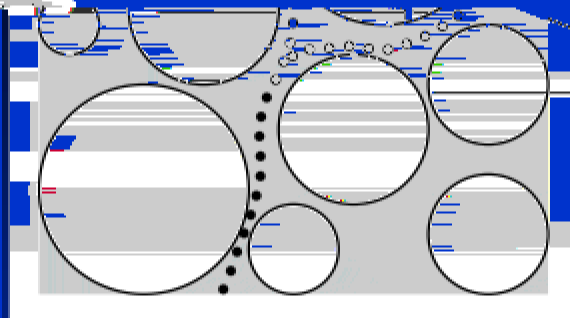
s. Buffering and
porous system.

lly sum of equal
us and isotropic

tical samples of
terial very small

eristics showing
r same material





Answer in g

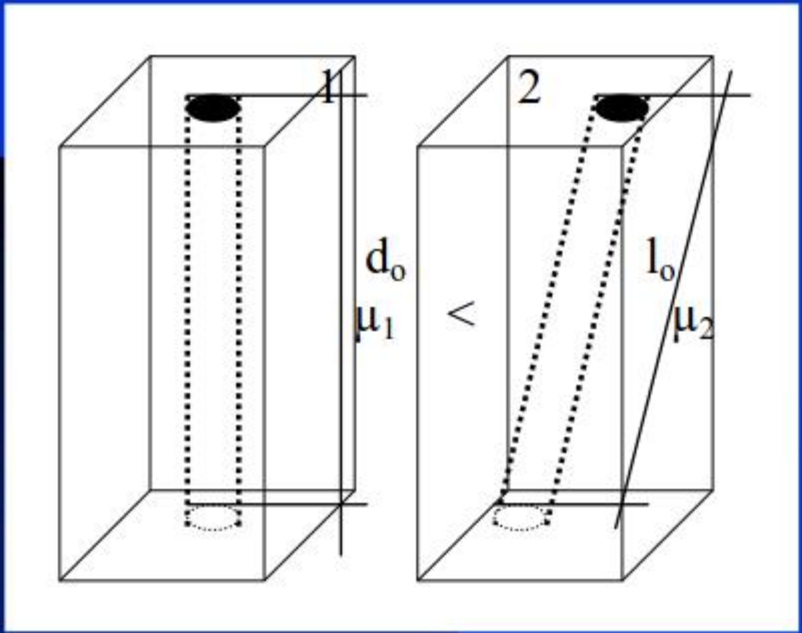
Very clear when mass related ch

Mass flows develop in the pores
flow characteristics typify

Porous systems only accidental
REV's, i.e. homogeneo

So: probability of getting iden
same mat

Or, measured mass related characte
large spread fo




# Weaknesses in actual modelling

Material properties

Example: water vapor resistance factor

Characterizes impact of porous system on water vapour flow by diffusion.

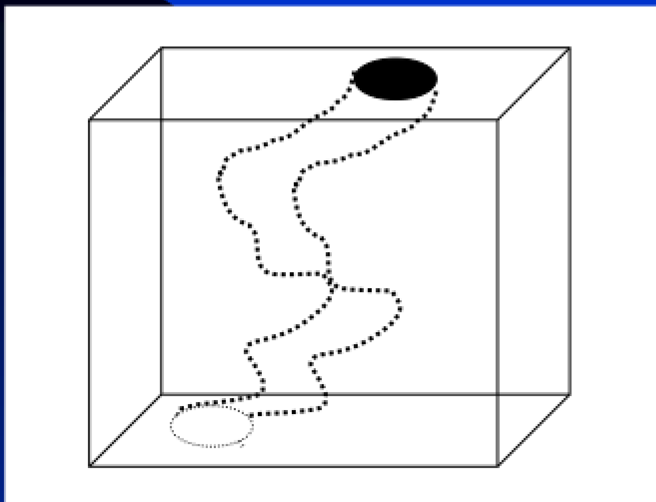
Defined as: $\mu = \frac{\delta_{v,a}}{\delta_v}$

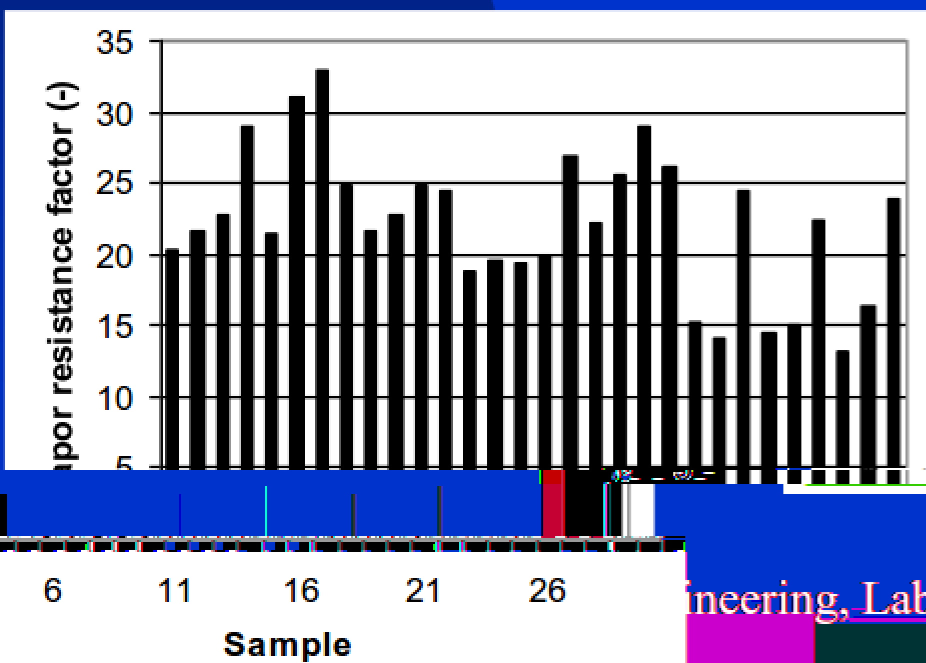
Straight pores with constant section perpendicular to the surface: $\mu = \frac{1}{\Psi_o}$

Straight pores with constant section slope $\alpha$ with the surface: $\mu = \frac{1}{\Psi}\left(\frac{1}{\cos\alpha}\right)$

# Weaknesses in actual modelling

## Water vapor resistance factor






Straight pores, angle α, varying section

$$\mu = \frac{1}{\Psi}\left\{\frac{\Psi}{\cos\alpha}\sum_{i=1}^{n}\left[\sum_{j=1}^{m}\left(\frac{d_j}{A_j}\right)\right]\right\}$$

In general: $\mu = \frac{1}{\Psi}\Psi_T$

with $\Psi_T$ tortuosity

$\Psi_T$ may vary substantially between samples of same material

# Weaknesses in actual modelling

## Water vapor resistance factor

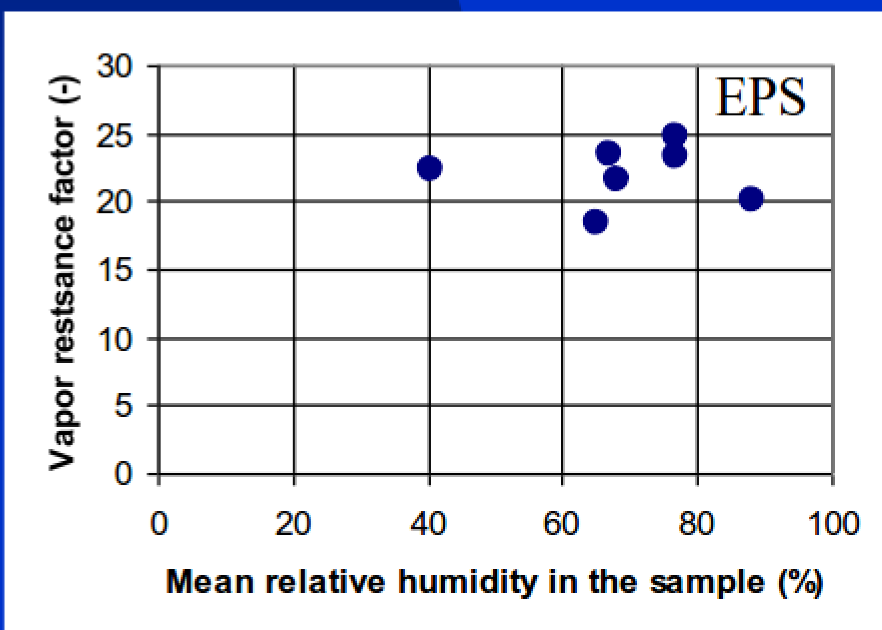
Anyhow, μ expected constant for given sample

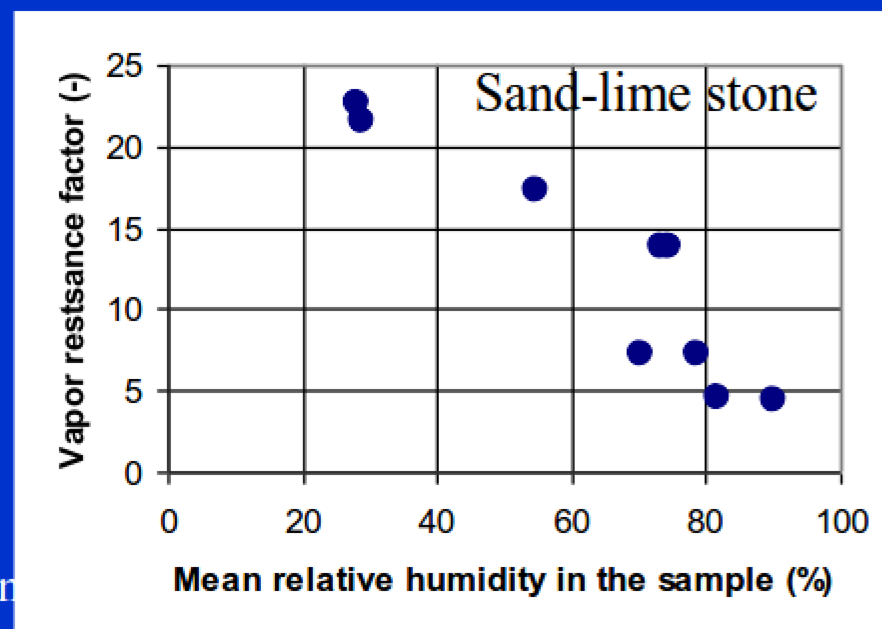
Not so for hygroscopic materials

Decreases with increasing relative humidity!

Also that relationship differs between samples.

Even function of temperature!



# Weaknesses in actual modelling

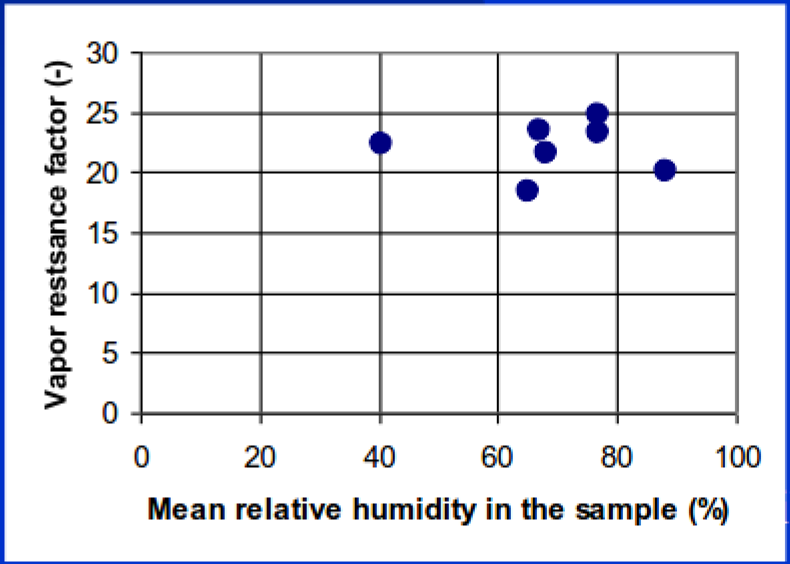
## Water vapor resistance factor

With n samples tested, how to calculate average μ-value?

Not as: $\mu_m = \frac{\sum \mu}{n}$, but

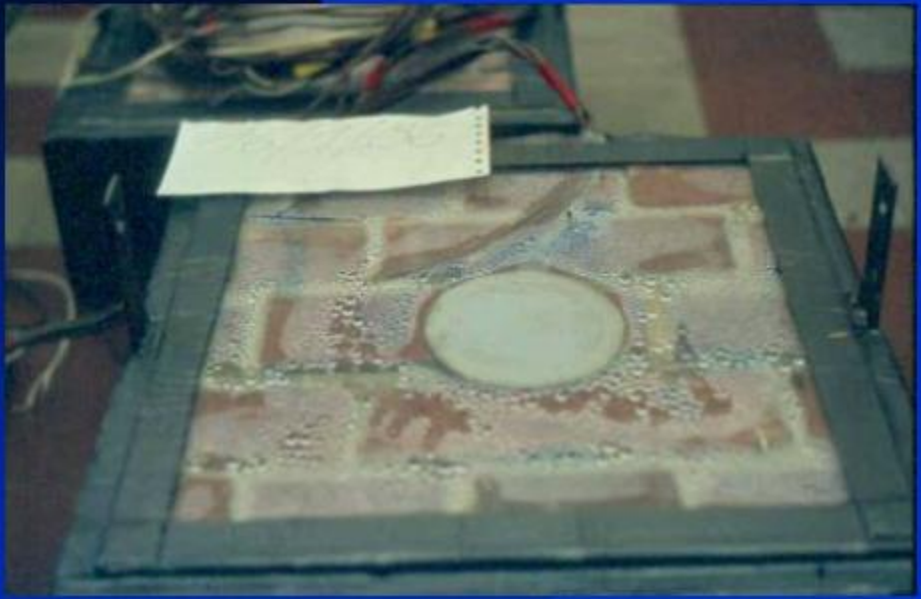
If sample thickness equals material thickness: $\mu_m = \frac{n}{\sum 1/\mu_i}$

Otherwise: $\mu_m = \frac{1}{n_2}\sum_{j=1}^{n_2}\left(\frac{n_1}{\sum_{i=1}^{n_1} 1/\mu_i}\right)$



# Weaknesses in actual modelling

Water vapor resistance factor



Complexity still grows when composite layers are considered

Take veneer wall

Why such low values?

Cracks between blocks and head joints, voids in mortar joints

| Wall | Mean RH<br><br>% | Diffusion resistance factor blocks, μ<br>- | Diffusion resistance factor veneer wall, μ<br>- |
|---|---|---|---|
| 1 | 59 | 50 | 3.0 |
| 2 | 57 | 50 | 3.2 |

# Weaknesses in actual modelling

Contact resistances between layers

Almost never considered but reality

Different contacts:

Ideal (continuity holds)

Air layer (diffusion only, capillary transport blocked)

Real (pattern of voids and capillary contacts, contact layer different from bulk layers)

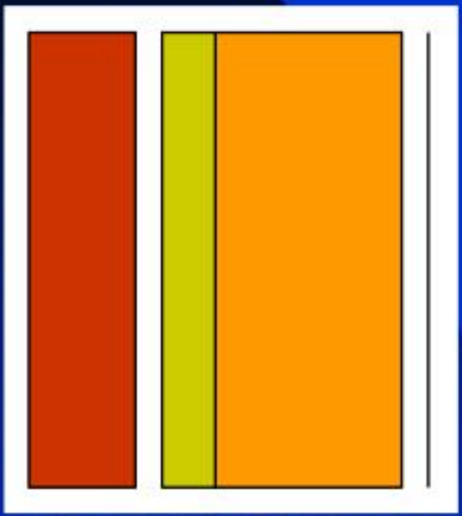
Problem: each situation different!

Contact resistances retard moisture transport between layers

Thin air layers, however, may promote air ingress, be capillary active and help gravity flow

# Weaknesses in actual modelling

Cavity wall, as implemented in 1D models

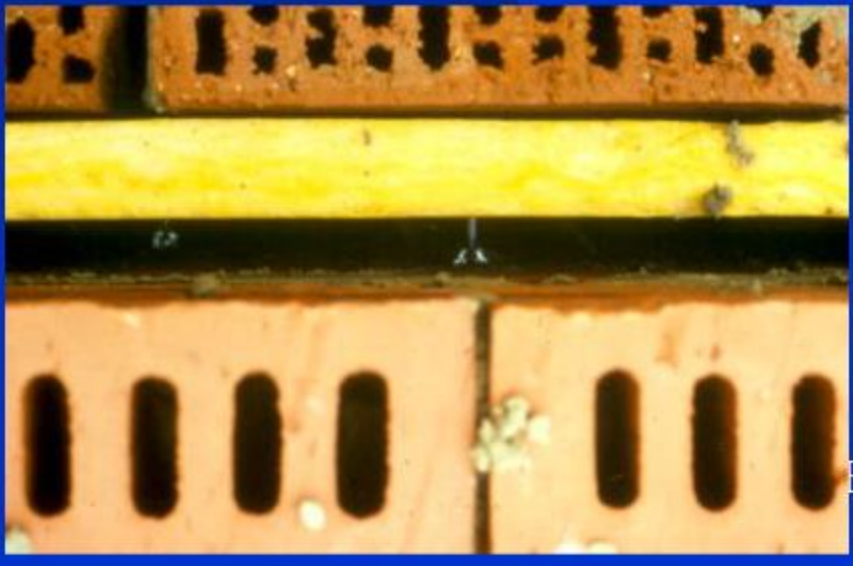


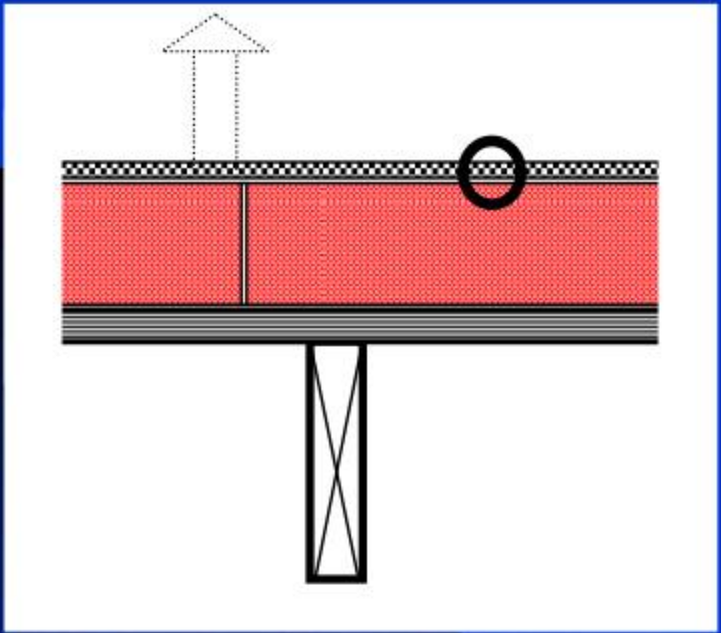
## Geometry

Geometry used when applying models always virtual picture

Reality very different

Where virtual picture is evaluated on HM transport, real part see HM plus air washing and gravity flow





# Weaknesses in actual modelling

Geometry

A simple one-dimensional roof section on paper

Turns out behaving in a three-dimensional way.

Why?

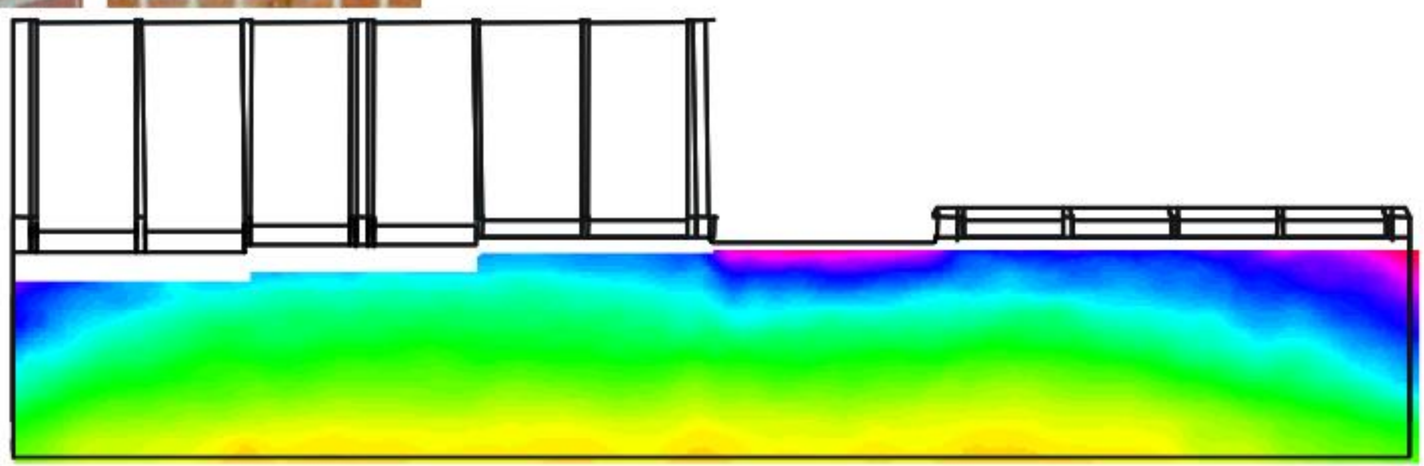
Vents

# Weaknesses in actual modelling

## Rain run-off

Rain impingement quite well predictable using CFD and droplet tracing

Learns that top corners and top zones see more wind driven rain than lower zones

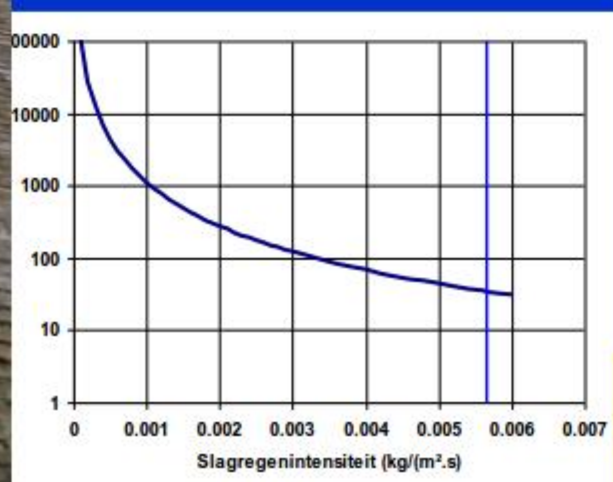


# Weaknesses in actual modelling

## Rain run-off

Rain hitting a surface
partially sucked
partially evaporates
partially runs of
Sucked water no problem
Run off main cause of rain leakage.

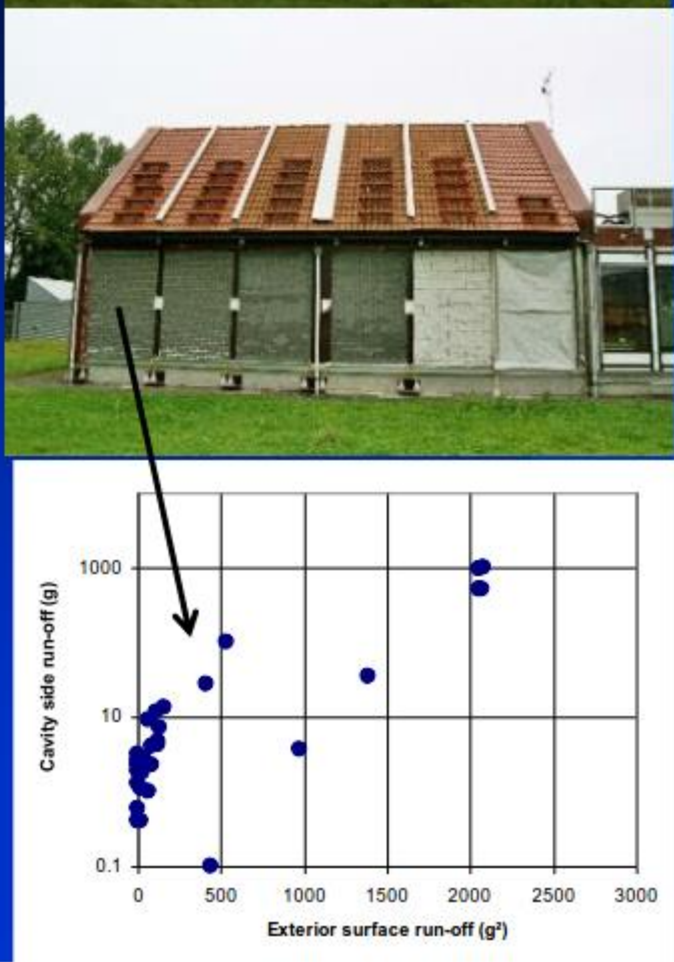
Run off mechanism and patterns difficult to predict. Water coming down may dilute or concentrate




$$t_r = 0.62 \frac{A^2}{g_{ws}^2}$$

# Weaknesses in actual modelling

## Wind pressure inducing moisture flow




Part of a main problem: accounting for pressure differences as cause of moisture flow

Wind presures helps in pushing rain run-off to the cavity side through cracks between head joints and bricks

Experimental formula (Vos, 1976)

$$G_{rsp} = 2.15 + 0.196 G_{rv} + 0.0308 \Delta P_a + 0.0017 G_{rv} \Delta P_a$$

# Weaknesses in actual modelling

## Gravity effects

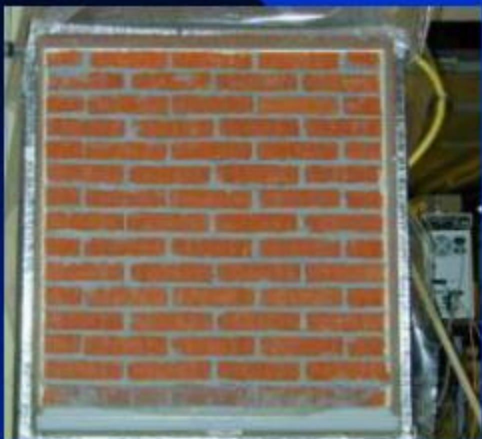
Gravity forces much stronger than wind

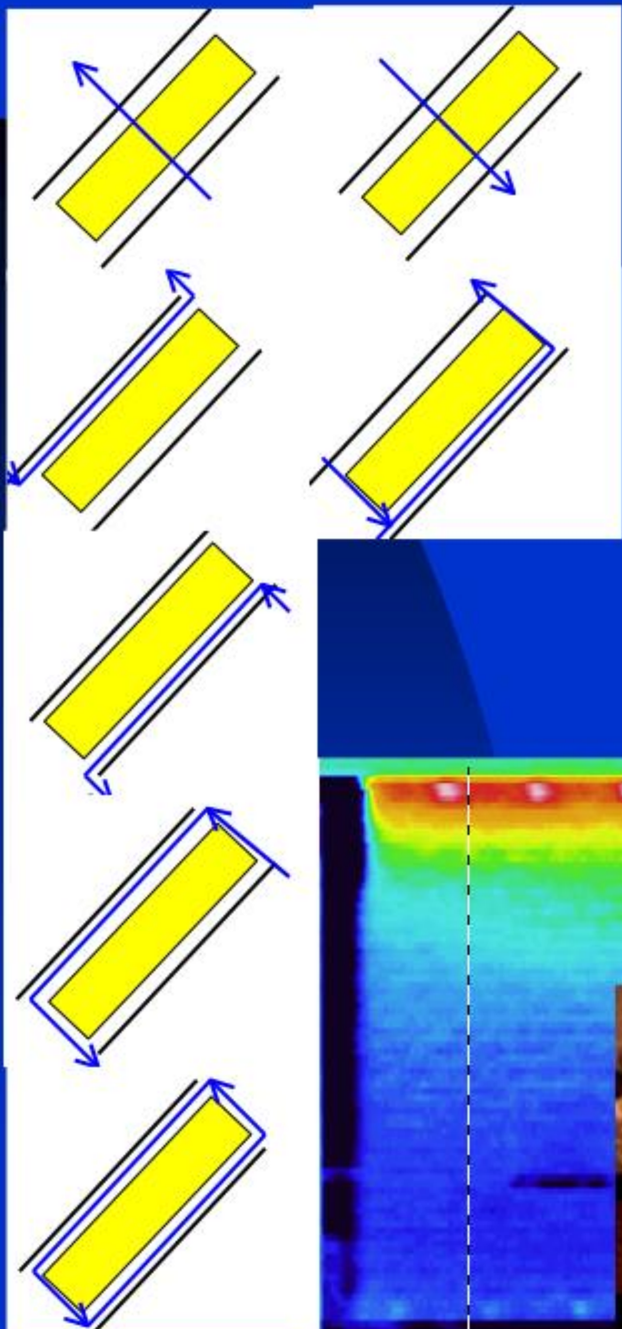
Induce analogous problems: leakages through joints, cracks, holes, voids, etc

Back to experimental formula for veneer leakage

Constant underlines importance of gravity

$$G_{rsp} = 2.15 + 0.196 G_{rv} + 0.0308 \Delta P_a + 0.0017 G_{rv} \Delta P_a$$



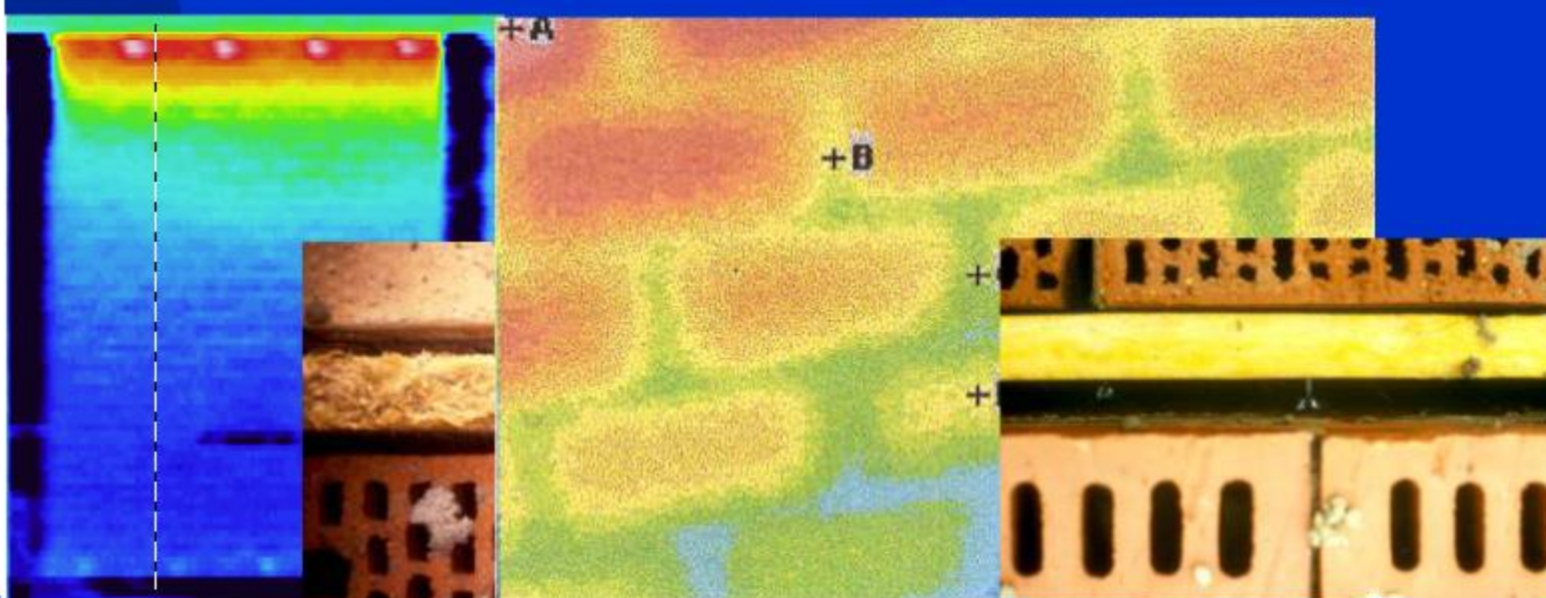


# Weaknesses in actual modelling

## Air flow

Although well known as a phenomenon, correct simulation highly random

Main reason: lack of knowledge on real geometry, included cracks, air layers, voids, etc



# Weaknesses in actual modelling

Not considering risk!

Risk: probability event will happen multiplied with severity of consequences

Randomness caused by uncertainty on influencing parameters

Future outside climate

Inside vapour release

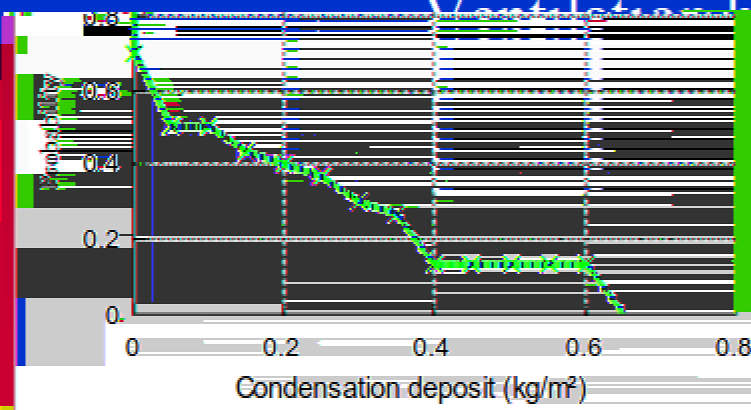
Ventilation habits

Air pressure differences

Workmanship

Design weaknesses





# Practice example

Large university building

Program demanded for underground parking, large lecture rooms, library, smaller seminar rooms and individual office rooms

Solved by lay-out which narrows from basement to top. Large lecture rooms below, library above, seminar rooms and offices on top

Result: building with oblique façade walls till the two highest floors

Cavity walls, oblique inside leafs in concrete

# Problems faced

Severe cracking

Abundant traces of water penetrations under all windows, and in the middle of the walls

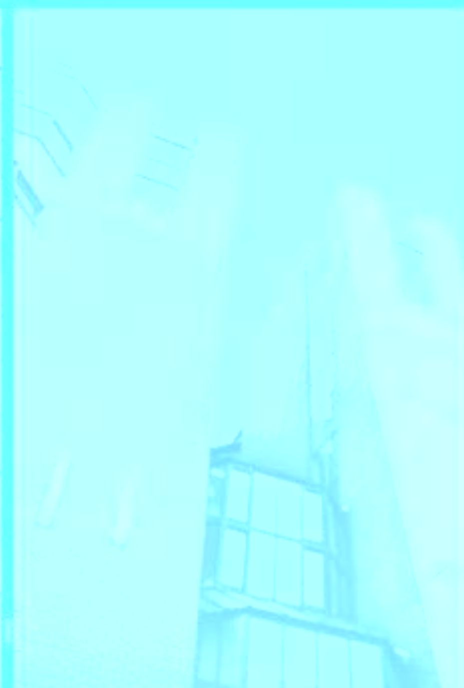
# Problems faced

View on oblique facade during rain shows run-off

Collects where the higher vertical facade touches the oblique part, provisional crack repair

Concentrated run of between oblique parts and window bays

Very intense run-off above the income hall



# Problems faced

Intensive moss growth in the joints of the oblique veneer walls

Window sill wrongly detailed, drains water to the window frame, where no edge below is detailed that halts the water

Oblique veneer not bonded, favors buckling!

# Analyzing the causes

Major cause: exposure to precipitation

Building form results in high wind-driven rain concentration on several surfaces

Oblique veneer walls even capture rain under windstill conditions

Water-repellant treatment increases water-load on mortar joints

Leaking water collects in the cavity, penetrates the insulation layer and humidifies the concrete inside leaf, where run-off bypass shrinkage cracks

Wall insulation facilitated veneer masonry cracking

# Repairs

First proposal

Repacing oblique parts by stepwise retiring façade walls

May solve rain penetration problem

One bay finished

But

Veneer walls not raintight

Cavity leakage collects on concrete steps, could drain to the inside

Quite severe thermal bridging were concrete steps penetrate thermal insulation

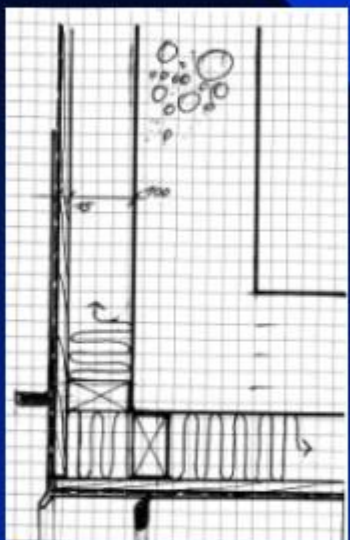
# Repairs

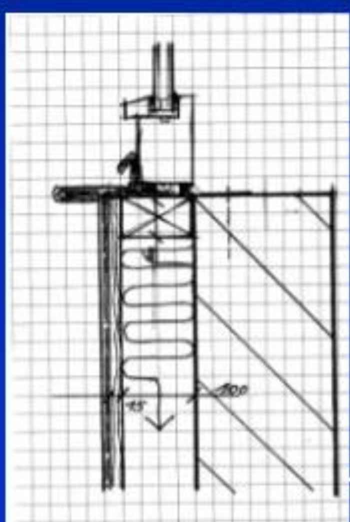
Second proposal

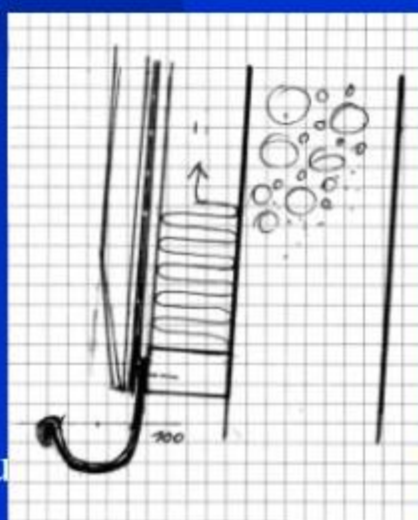
Demolishing oblique veneer walls

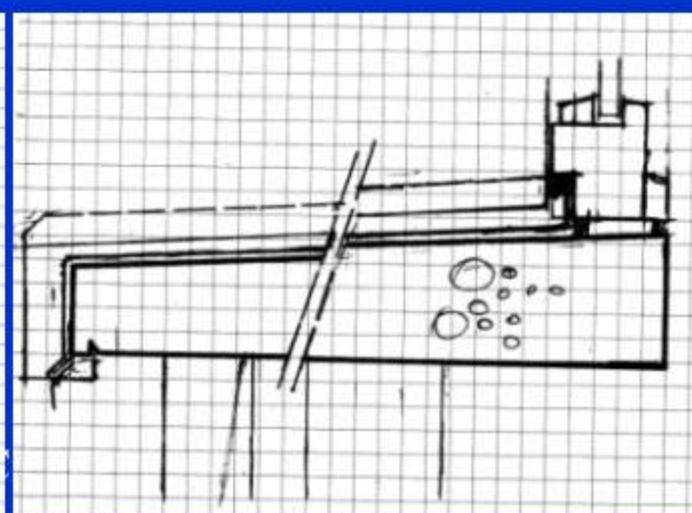
Standing seam zinc cover instead

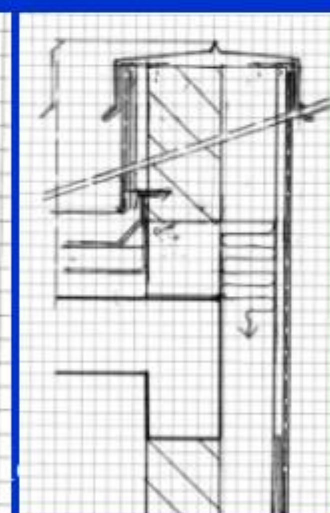
Correct detailing very important, must solve whole bunch of problems without introducing new ones, such as reinforced thermal bridging, backside interstitial condensation, a.o.











# Conclusion
# How to become an expert in HAM?

but additionally, by testing and gaining field experience

Not by studying only