STRUCTURAL ASSESSMENT AND INTERVENTION APPROACHES FOR HISTORIC STRUCTURES

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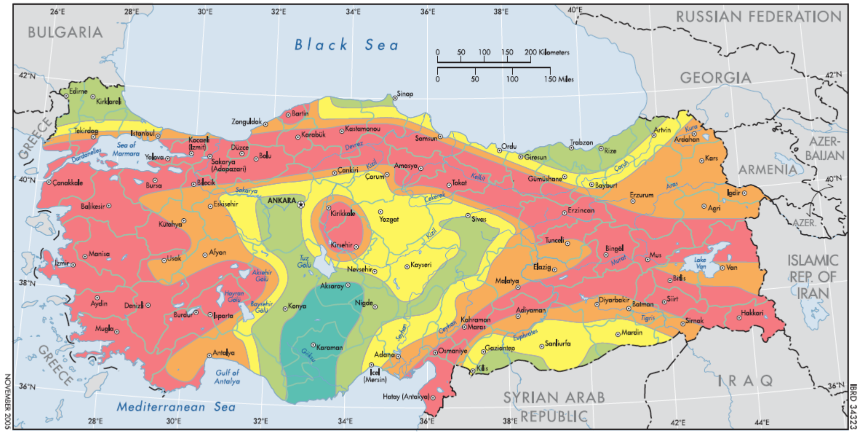
Why the historic structures need structural rehabilitation?

- Mainly due to:
  - The existence of visible defects and deteriorations
  - Damage after particular events (such as fires and earthquakes)
  - The change of use that would cause a significant increase in the loads
  - Performance requirements of the authority or the owner

- The structural rehabilitation of heritage buildings has implications of architectural, structural, economic, historic and social order
- Consequently; conservation, reinforcement and restoration of architectural heritage requires a multi-disciplinary approach.

Ispir et al., 2006

- Many historical assets under the risk of seismic actions.
- However, the exisiting engineering literature is quite scarce on seismic behavior of these structures



Ürekli, 1999

THE BASIC APPROACH IS SIMILAR TO WHAT IS USED IN MEDICINE (ISCARSAH, 2003)

Multidisciplinary decision making for all steps

Anamnesis

- Site investigations (geometry, loads, damages, etc.))
- Literature survey and historic data
- Construction methodology and material characteristics
- Site and laboratory tests

Diagnosis

- Current and historic data on damages and interventions
- Structural analyses (FEA, hand calculations, limit state analysis)
- Monitoring of the structure
- Safety evaluation, weak points

Theraphy

- Should adress root causes rather than symptoms
- Best theraphy is preventive maintenance
- No actions without demonstrating that they are indespensable
- Iterventions should be least invasive and most compatible with the heritage values
- Improve rather than retrofit

Controls

- Interventions and the structure should be controlled before, during and after the execution
- All activities of checking and monitoring should be documented and kept as part of the history of the structure

Any standards or guidelines for historical structures?

In addition to international charters (i.e. Venice Charter):

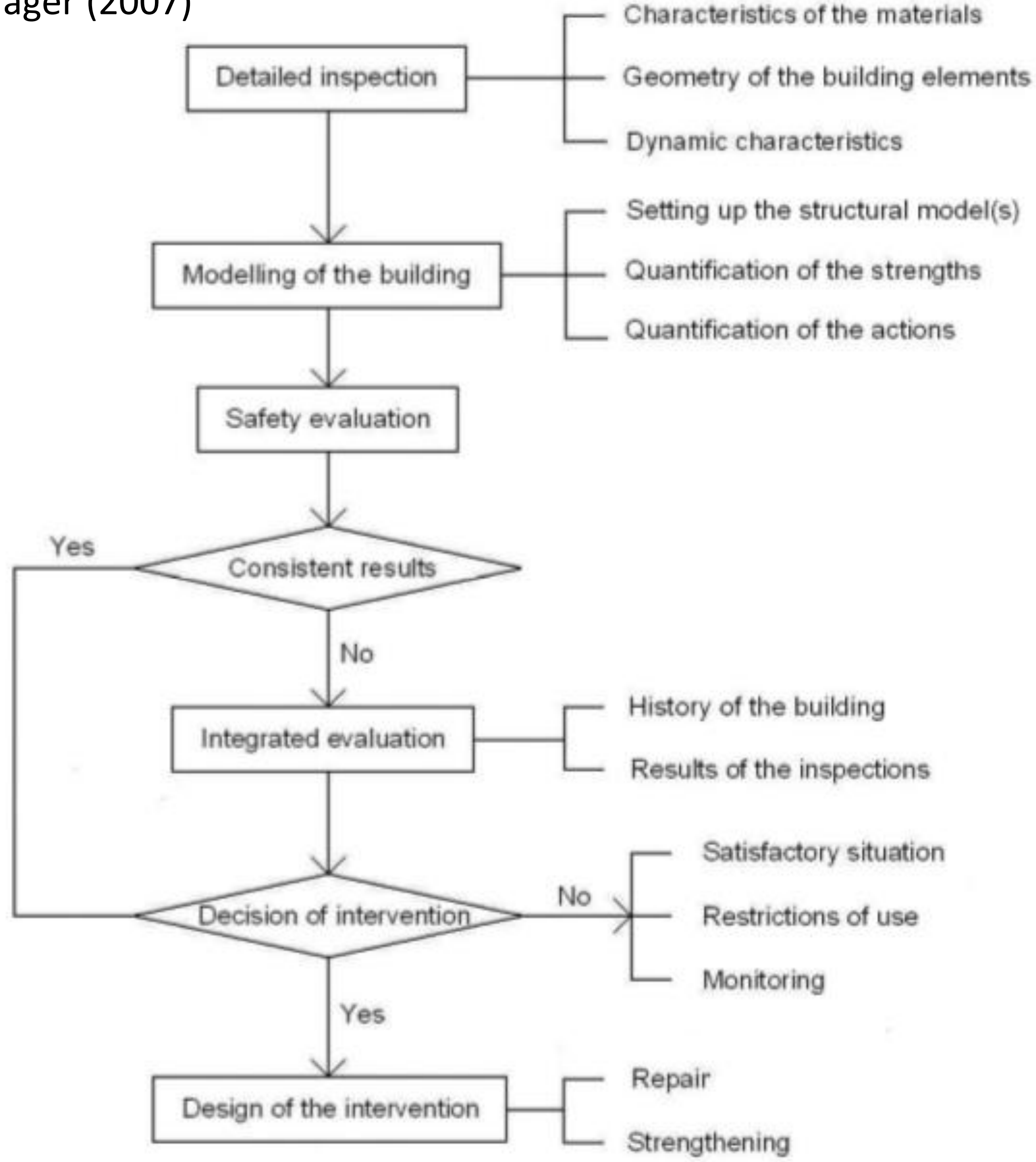
- ISO 13822: Basis for design of structures, an annex for historical structures is provided
- ISCARSAH Principles for the analysis, conservation and structural restoration of architectural heritage (2003)
- Seismic design and assessment documents (i.e. EN 1998-3 Eurocode 8, ASCE 41-13, TSDC 2007, NTC 08, etc)
- Specific guidelines for historic structures (i.e. Italian, Turkish guidelines)

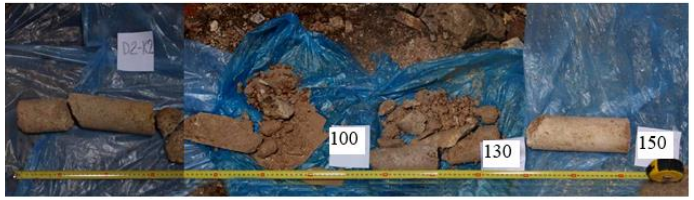
GUIDELINE FOR EARTHQUAKE RISK MANAGEMENT OF HISTORICAL STRUCTURES IN TURKEY (2017)

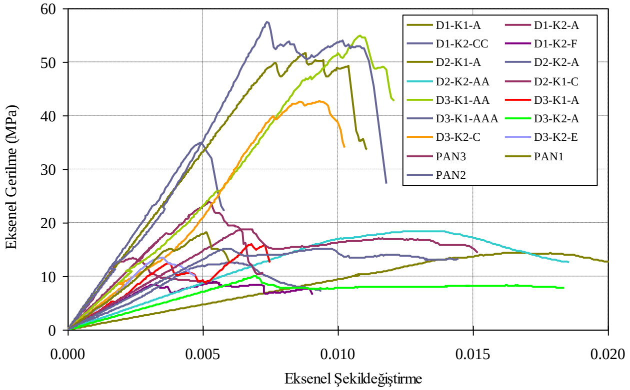
Structural Assessment

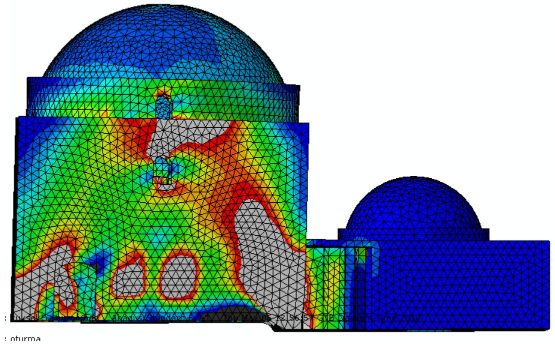
Flowchart for Structural Assessment

From Jager (2007)









Static linear analysis; dynamic modal (linear) analysis; nonlinear static (pushover) analysis; and, non linear dynamic analysis

Actions and loads to be considered

- Self weight
- Live loads
- Seismic loads
- Wind, snow, ice loads
- Temperature effects
- Soil settlements

Soil settlement during
tunnel construction

Structural Assessment of Historic Structures

Great diversity of construction materials and techniques

Lots of uncertainties

Long ago forgotten aspects

Difficulties in data collection

Lack of guidelines

Difficulties in modelling and analyses

Difficulties in determination of demand

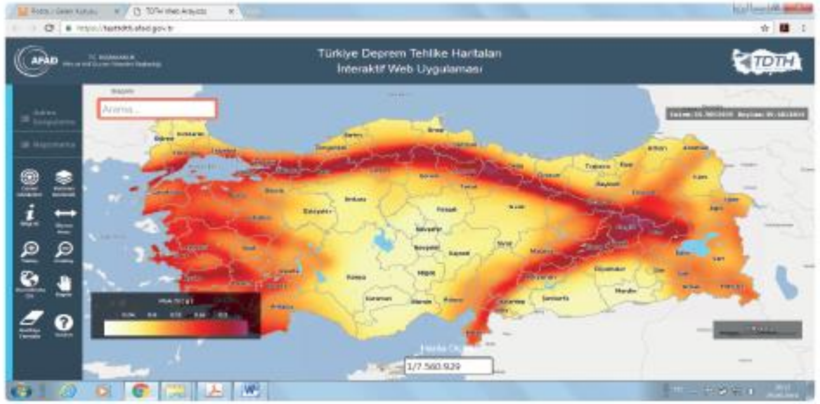
Difficulties in determination of expected performance

Seismic Demand

- Different seismic intensity levels can be defined as also done for new constructions:
  - Extremely rare ground motion with a probability of exceedance of 2 % in 50 years with a return period of 2475 years (DD-1, Maximum Considered Earthquake),
  - Rare ground motion with a probability of exceedance of 10 % in 50 years with a return period of 475 years (DD-2, Design Earthquake)
  - Occasional ground motion with a probability of exceedance of 50 % in 50 years with a return period of 72 years (DD-3, Service Earthquake).
- But should we consider the same hazard levels as we do for new constructions?
- Sometimes 60-80% of new constructions can be OK

DD1 - PGA

DD2 - PGA

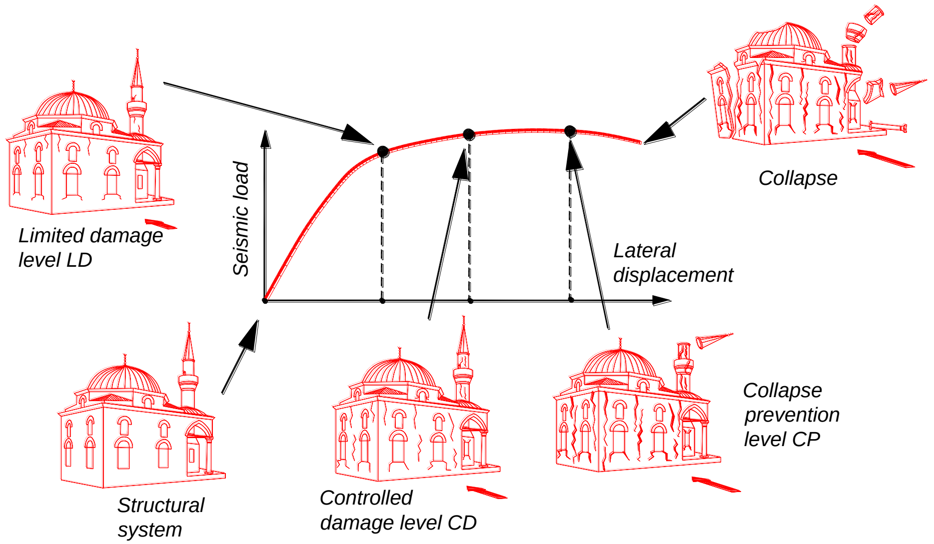


DD3 - PGA

Turkish Seismic Hazard Map (https://testtdth.afad.gov.tr/)

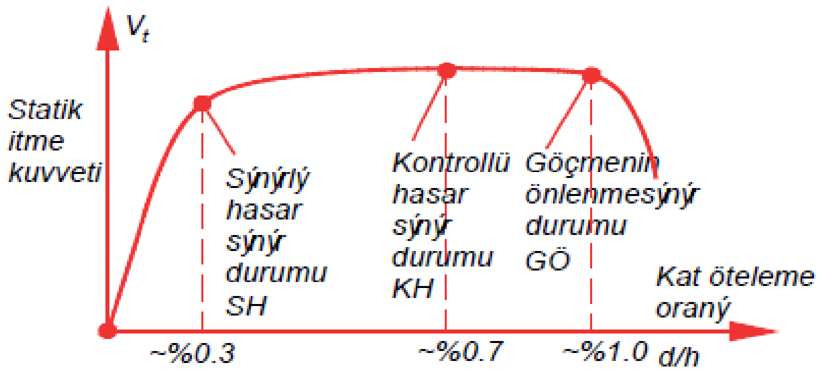
Damage states

- Definition of damage states that is applicable to all types of historic structures is not easy
- Not an easy task to express these requirements in a mathematical form
- In many cases even not easy to differentiate structural and non-structural elements
- In Turkish Guidelines:
  - Limited damage level (LD): The structure is assumed to be almost in the elastic region or just above it, fine cracks in the structural elements is tolerable
  - Controlled damage level (CD): The structure can be repaired and retrofitted without extensive interventions
  - Collapse prevention level (CP): Damage state is just before the collapse (difficult to define brittle structural systems)



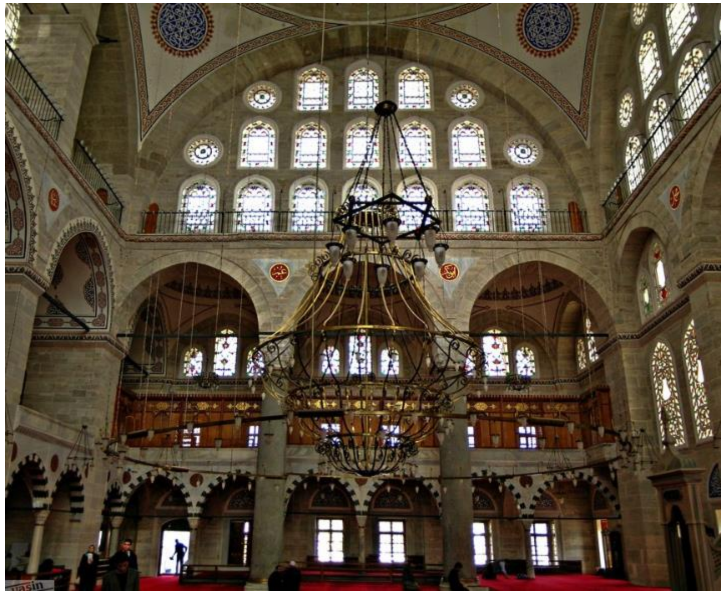
Method of analysis and limits for damage states

- Linear vs. non-linear analysis
- Static vs. dynamic
- Linear procedures require less material data
- Non-linear procedures provide more information and claim to be more realistic
- Hand calculations or limit state analysis should not be underestimated
- In Turkish Guidelines the following analysis methods and damage state limits are recommended:



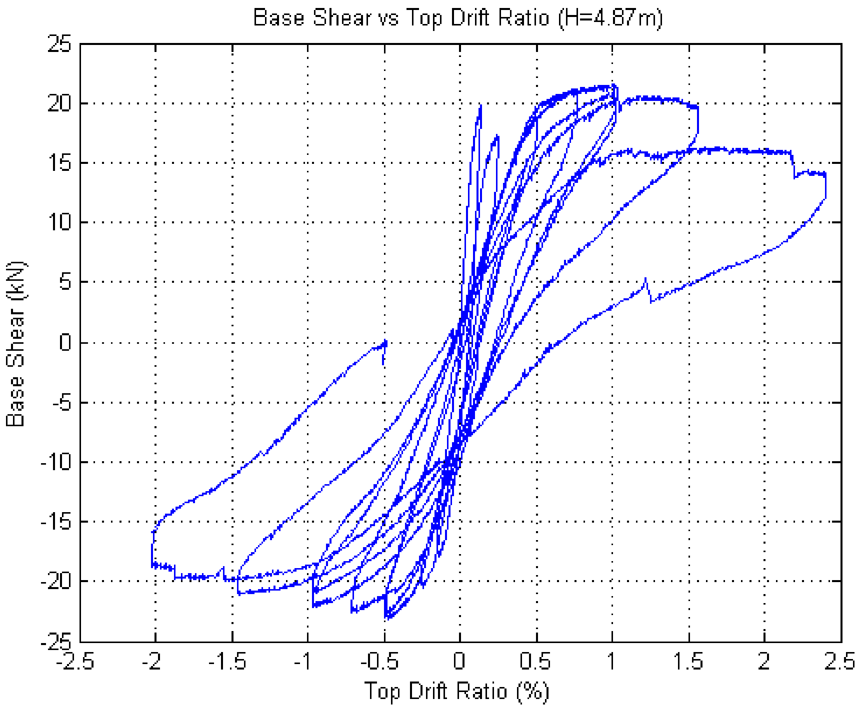
Performance levels	Methods of analysis / limits
Limited damage Level (LD)	Linear analysis is employed, a) ultimate stresses of the material or ultimate strength of the structural element and joints are not exceeded, when the structure is subjected to vertical and unreduced earthquake loads. b) Drifts do not exceed 0.3%, when the structure is subjected to vertical and unreduced earthquake loads.
Controlled damage level (CD)	1. Linear analysis is employed. a) Ultimate stresses of the material or ultimate strength of the structural element and joints are not exceeded, when the structure is subjected to vertical and earthquake loads reduced with $R_a \leq 3$, b) Drifts do not exceed 0.7%, when the structure is subjected to vertical and unreduced earthquake loads. 2. Nonlinear analysis is employed. a) Ultimate strains of the material are not exceeded, b) Drifts do not exceed 0.7%, when the structure is subjected to vertical and earthquake loads.
Collapse prevention level (CP)	1. Linear analysis is employed. a) Ultimate stresses of the material or ultimate strength of the structural element and joints can be exceeded with a certain ratio (i.e. 50%), when the structure is subjected to vertical and earthquake loads reduced with $R_a \leq 3$, b) Drifts do not exceed 1.0%, when the structure is subjected to vertical and unreduced earthquake loads. 2. Nonlinear analysis is employed. a) Ultimate strains of the material can be exceeded with a certain ratio (i.e., 20%) , b) Drifts do not exceed 1.0%, when the structure is subjected to vertical and earthquake loads.

Edirnekapı Mihrimah Sultan Cami – 16. century



25m

5m

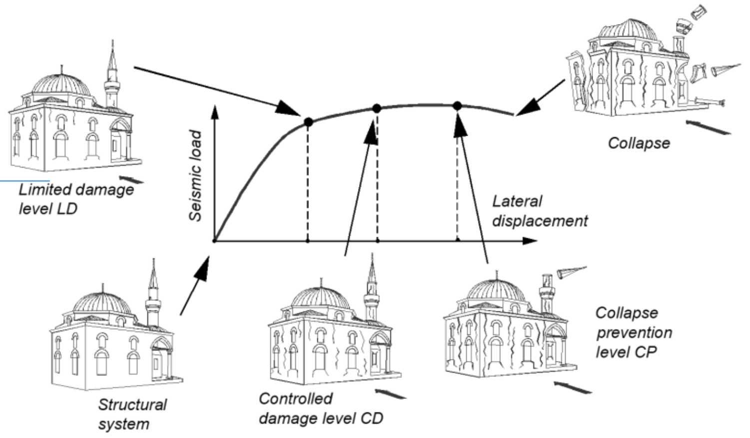


İTÜ-İSTKA 2015 Projesi – Yürütücü: Y.Doç.Dr. İ.E. Bal

Performance Targets

In Turkish Guidelines the following performance targets are recommended for structures with different importance levels:

Targeted performance levels	Nationally important historical structure (relatively moderate importance)	Internationally important historical structure (relatively high importance)	
	DD-3/LD	DD-2/LD	DD-1/LD
Locally important historical structures (relatively less importance)	DD-3/CD	DD-2/CD	DD-1/CD
	DD-3/CP	DD-2/CP	DD-1/CP



- Strict performance targets are demanded for all historical structures, particularly for important ones
- Strict performance levels may not be satisfied and when extensive structural intervention are required, it is very difficult, often impossible, to apply them
- It is more appropriate to choose at least two different performance targets. One of these targets can be more strict and compatible with the historical value and feature of the particular structure, whereas the other can be for a more relaxed performance target.
- The final decision can be made at the intervention stage by comparing the alternatives not only from the structural point of view, but also their applicability and compatibility with the architectural characteristics

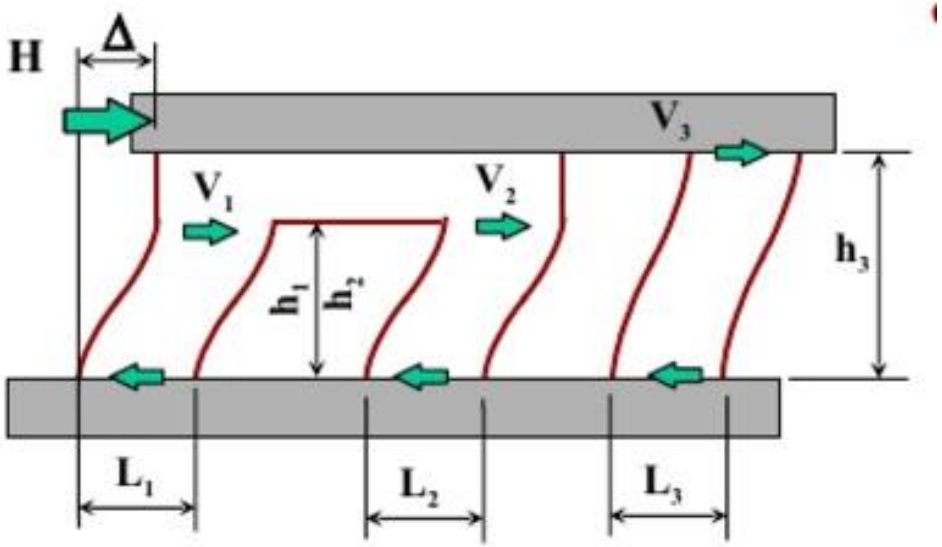
Modelling Approaches

a) Simple Wall Model:

Vertical loads are resisted by the net Wall area of each story

Seismic load acting to each story in two orthogonal directions is distributed to each wall with respect to their lateral stiffness and divided by the wall cross-section area.

The obtained shear stress is compared with wall allowable shear stresses depending on the material type.



Abrams (2004)

World Housing Encyclopedia

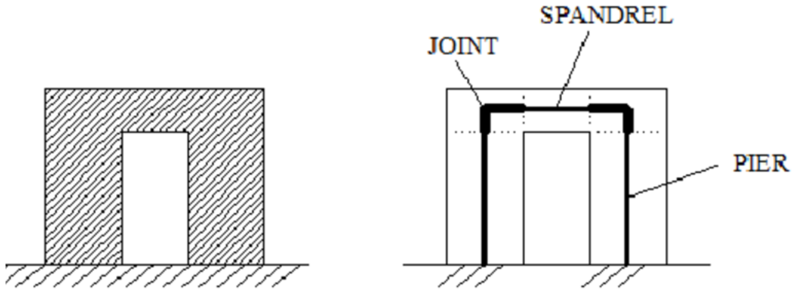
Modelling Approaches

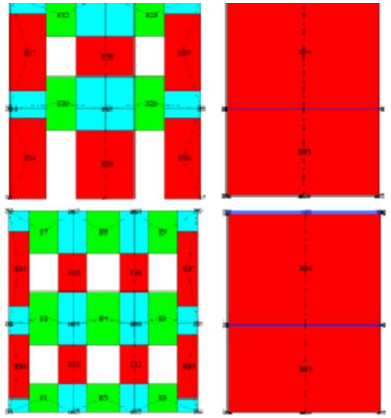
b) Equivalent Frame Model:

Frame elements capable of representing bending and shear behavior of masonry walls and spandrels are used.

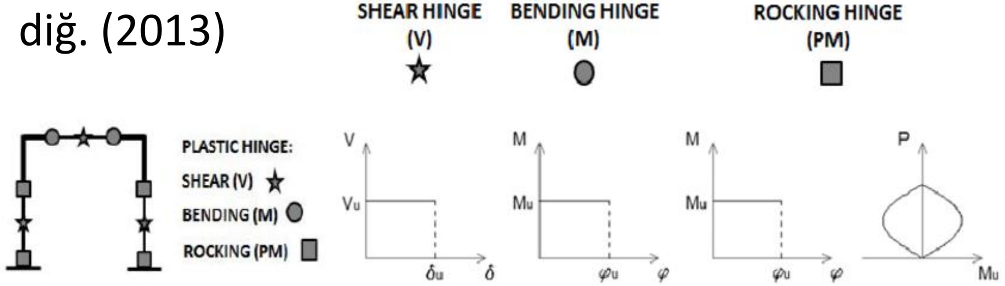
Since the approach is computationally inexpensive and familiar, this approach is appropriate for non-linear analyses.

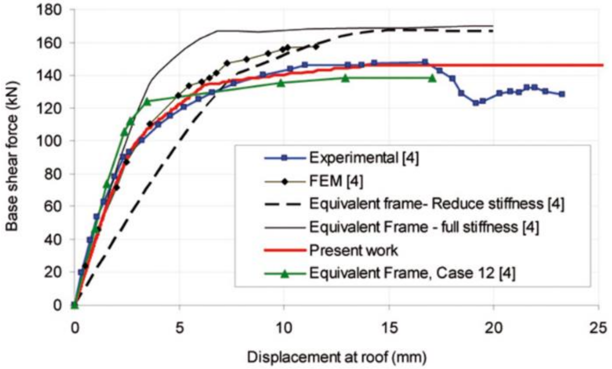
Idealization is important.





Bucchi ve diğ. (2013)



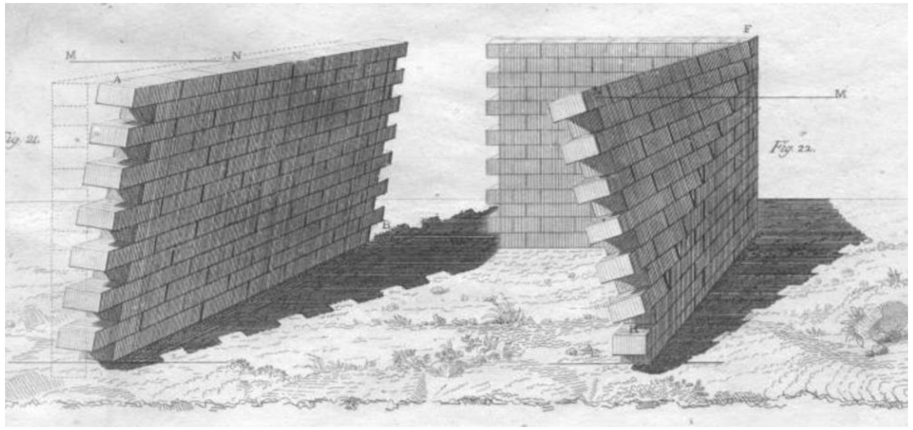


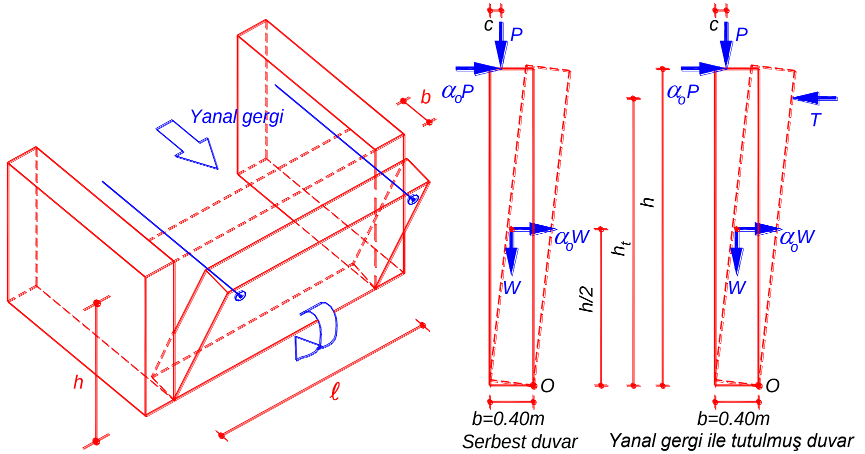
Modelling Approaches

c) Limit state analysis considering different mechanisms:

1. Definition of potential mechanism states for members and portions of the structure,
2. Determination of the seismic load factor that would activate each of the assumed limit states by using principle of virtual work and equilibrium equations.
3. Compare the load factors with the seismic demand
4. Decide on the intervention (i.e. addition of steel ties) and check the limit states again

Particularly recommended for out of plane failure modes of walls and façades!





TARİHİ YAPILAR İÇİN DEPREM RİSKLERİNİN YÖNETİMİ KILAVUZU

Modelling Approaches

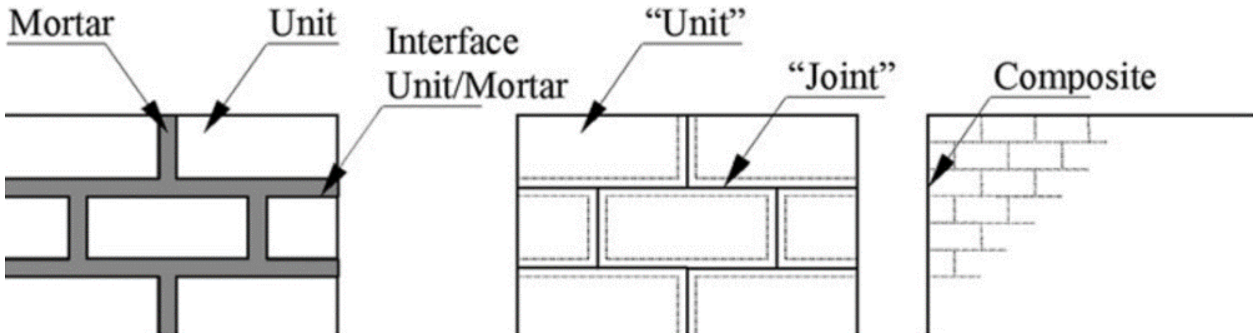
d) Finite Element Analysis:

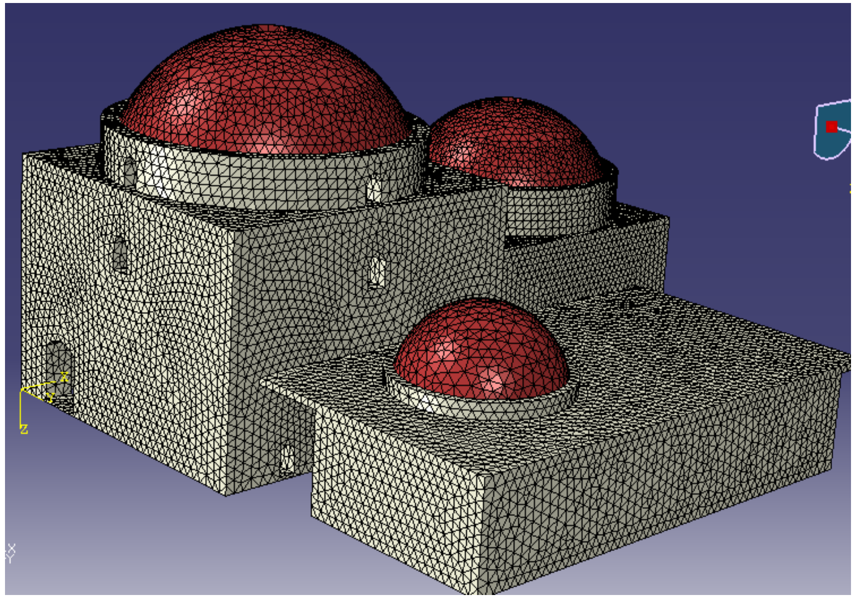
Gometry of the structure can be represented by using 1D, 2D or 3D elements.

Suitable for modelling of curved structural members such as domes and vaults.

Nonlinear behavior can be represented in the analysis.

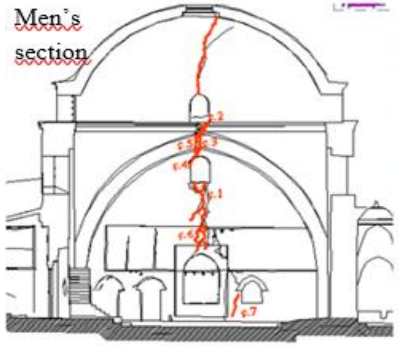
Micro, meso and macro level modelling can be done.

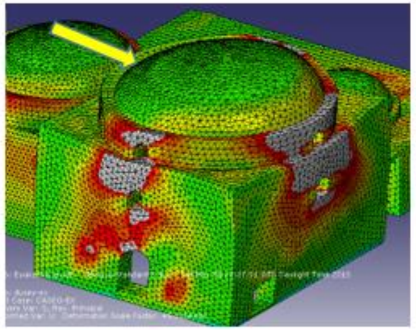


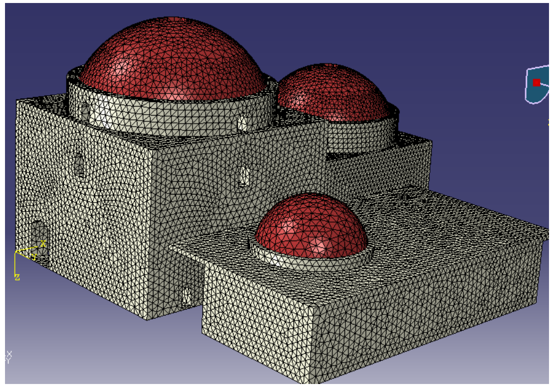


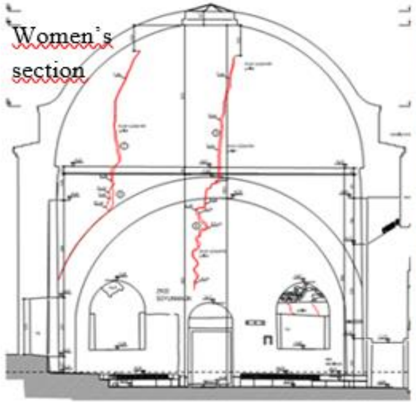
Example: Küçük Mustafa Paşa Bath Complex

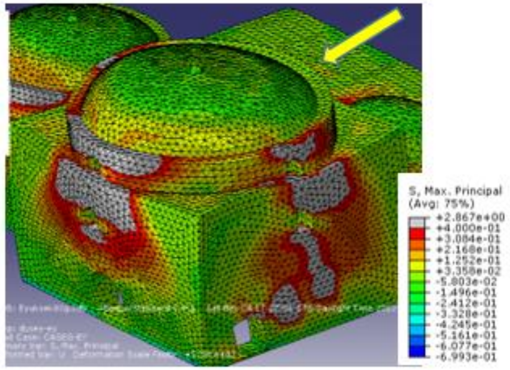
- Cibali, Istanbul
- 15th cent.
- 3D solid elements for modelling
- Vertical cracks on walls and domes





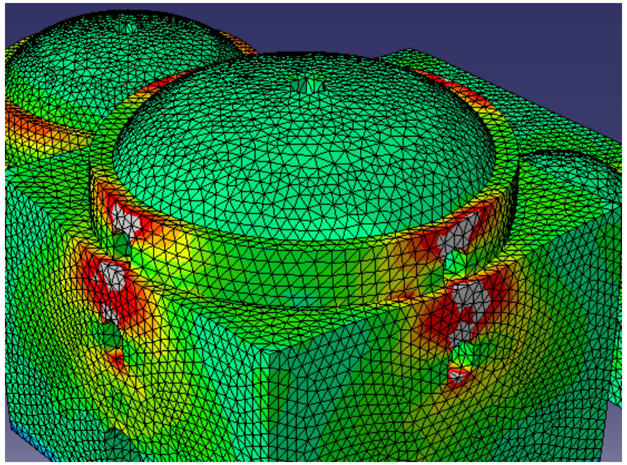


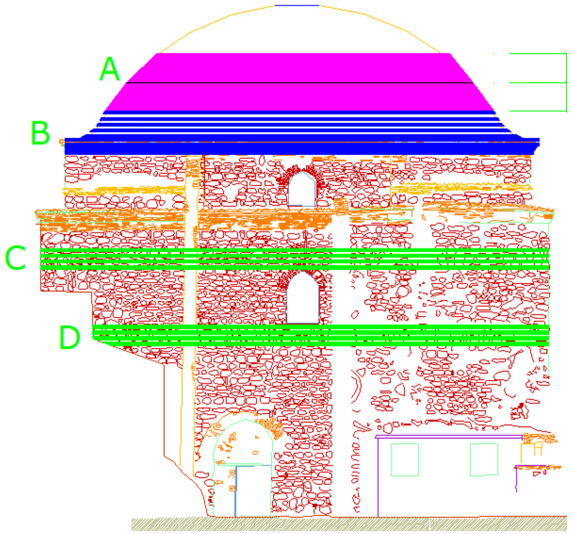




Example: Küçük Mustafa Paşa Bath Complex

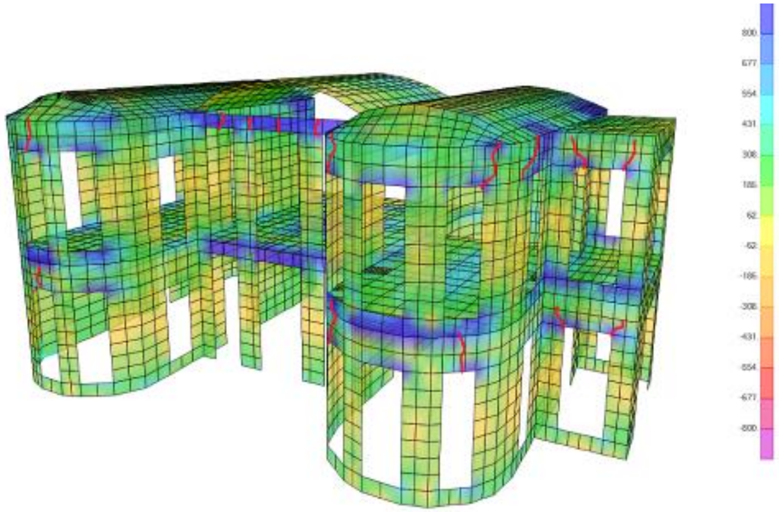
FRP sheets and rods applied to the domes and main exterior walls

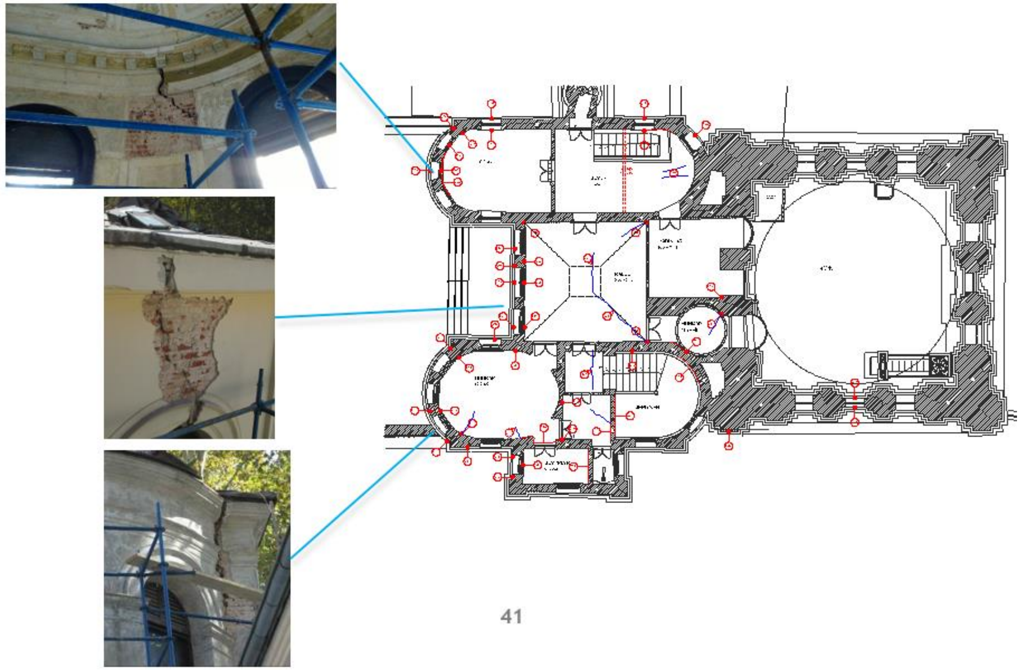




Example: Küçük Mecidiye Camii

- Ortaköy, Istanbul
- 19th cent.
- 2D shell elements used for modelling
- Cracks around window and door openings





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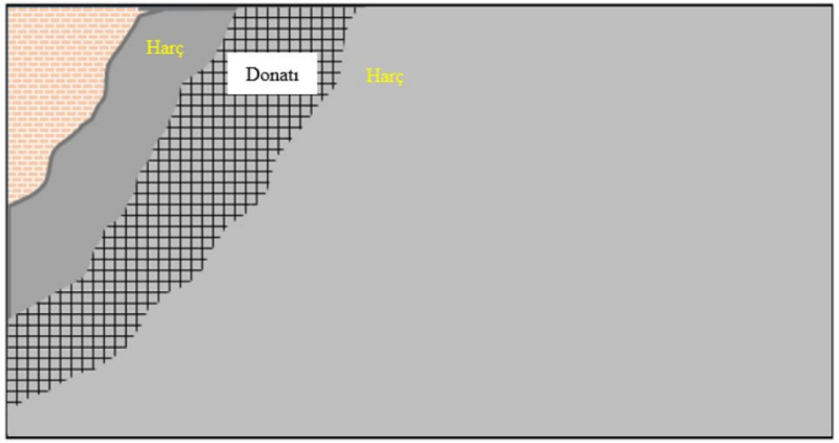
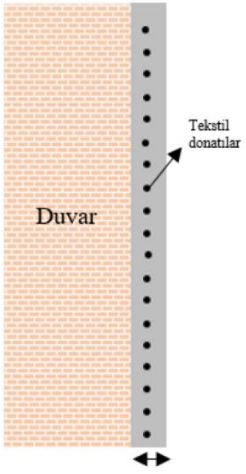
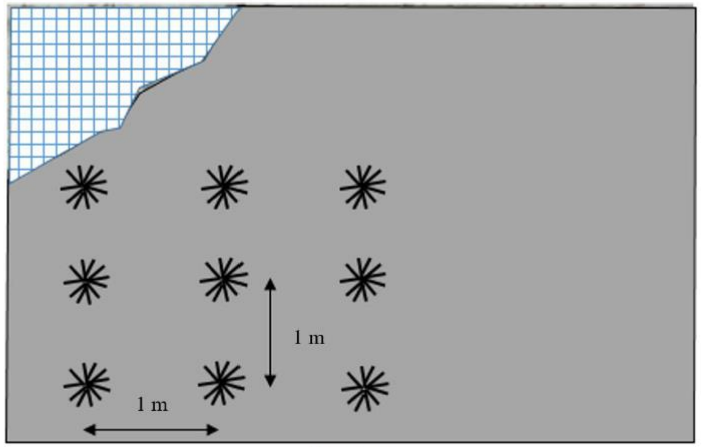
Example: Küçük Mecidiye Camii
Textile Reinforced Mortar (TRM) application



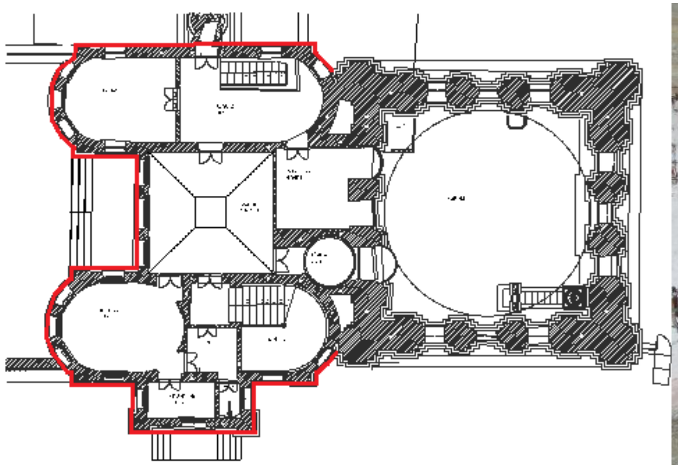
Yandan görünüş



Kesit

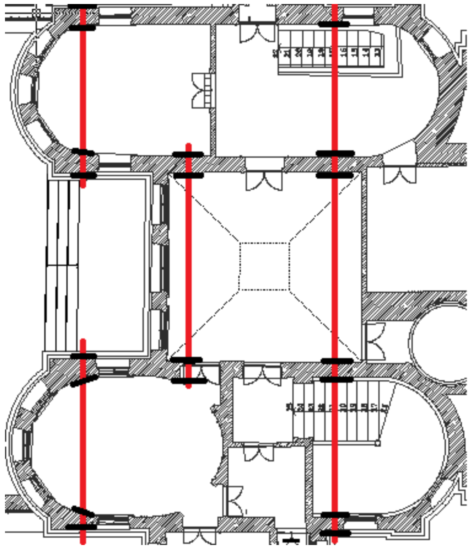


Düşey kesit



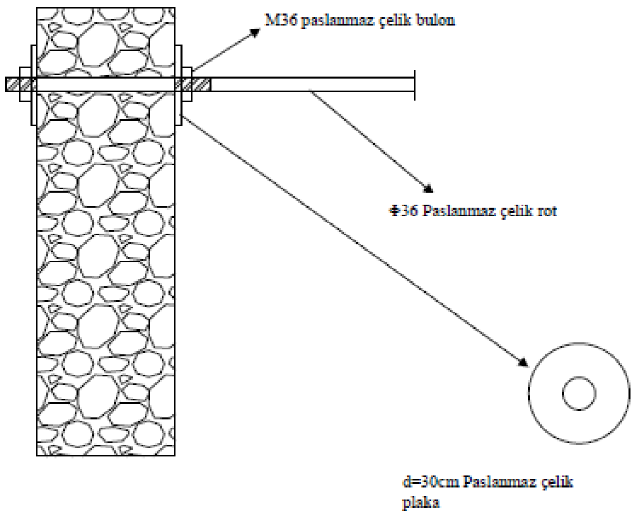
Example: Küçük Mecidiye Camii

Addition of stainless steel ties



Küçük Mecidiye Camii

EK 2 GERGİ ÇUBUKLARI



Material Properties

Materialwise, historic structures exhibit a great diversity

Not possible to classify the material characteristics as we do for concrete or steel

However, ranges of values obtained from site and laboratory tests are available:

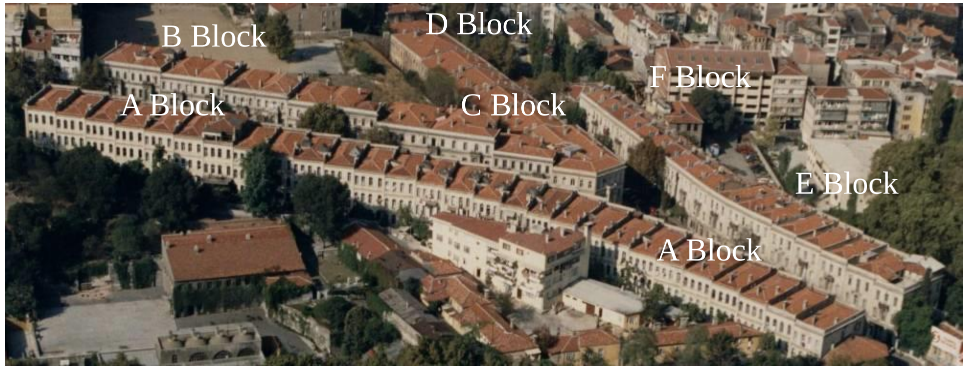
Masonry typology	f_m (N/cm^2)	τ_0 (N/cm^2)	E (N/mm^2)	G (N/mm^2)	W (kN/m^3)
	min-max	min-max	min-max	min-max	
Irregular stone masonry (pebbles, erratic, irregular stone)	100 180	2.0 3.2	690 1050	230 350	19
Uncut stone masonry with facing walls of limited thickness and infill core	200 300	3.5 5.1	1020 1440	340 480	20
Cut stone masonry with good bonding	260 380	5.6 7.4	1500 1980	500 660	21
Soft stone masonry (tuff, limestone, etc.)	140 240	2.8 4.2	900 1260	300 420	16
Dressed rectangular stone masonry	600 800	9.0 12.0	2400 3200	780 940	22
Full brick masonry with lime mortar	240 400	6.0 9.2	1200 1800	400 600	18
Masonry in half-filled brick blocks with cement mortar (e.g. double UNI, percent. of perforations ☐ 40%)	500 800	24.0 32.0	3500 5600	875 1400	15

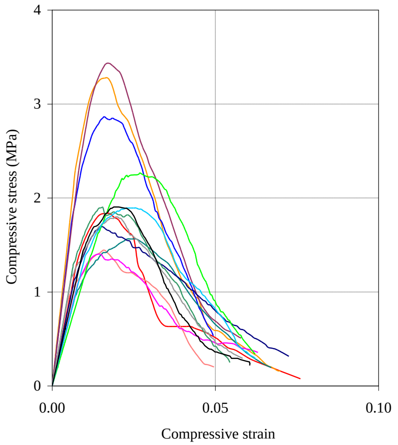
From commentary of Italian NTC08

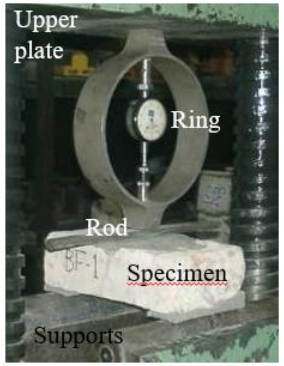
Tests at ITU

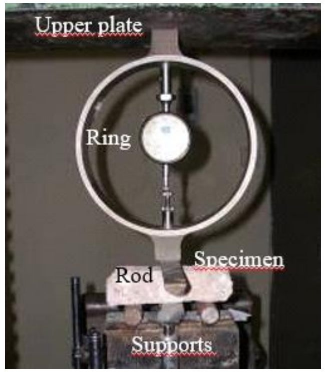
Material tests

Akaretler, İstanbul



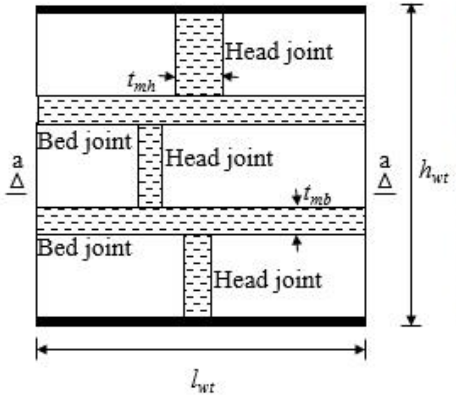






Tests at ITU

Wallet tests

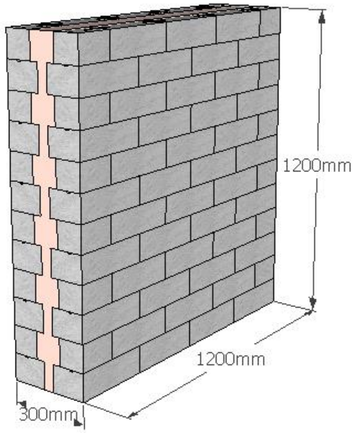


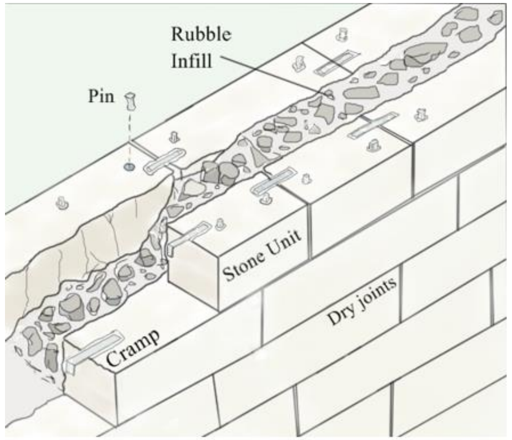
Source: Medine İspir

Source: Cem Demir

Tests at ITU

Wallet tests





(modified from Tanyeli, 1990)

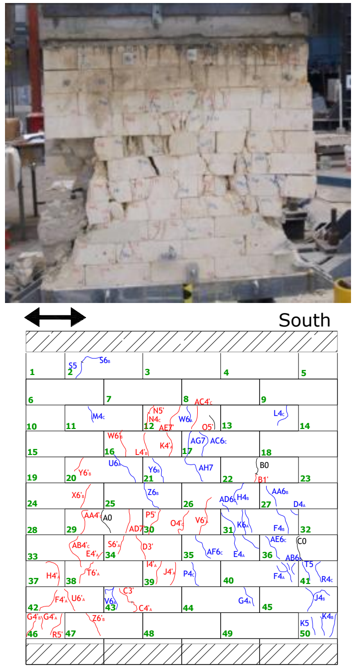
(Prof.Dr. İlknur Kolay)

Demir (2012)

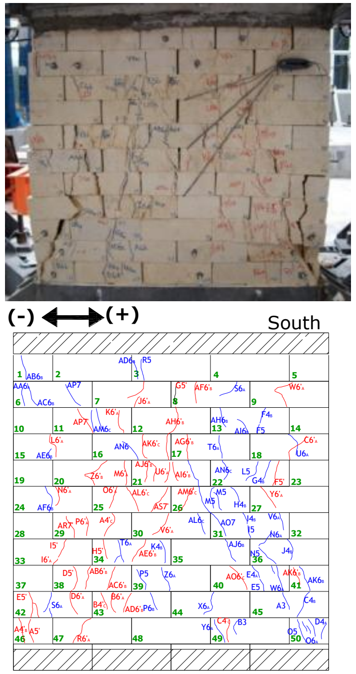
Tests at ITU

Wallet tests

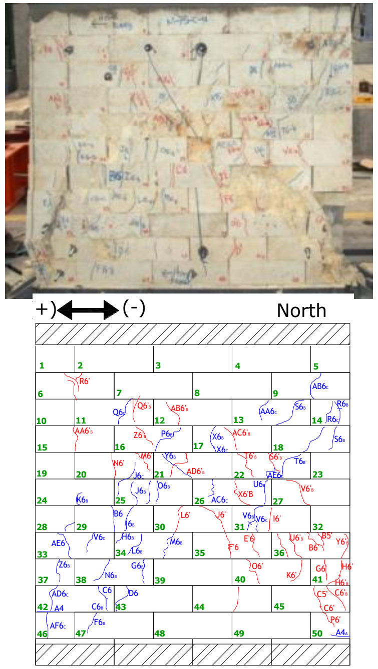
M-25-C



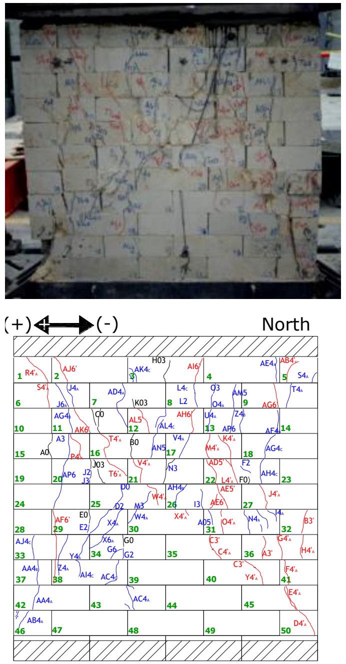
M-50-C



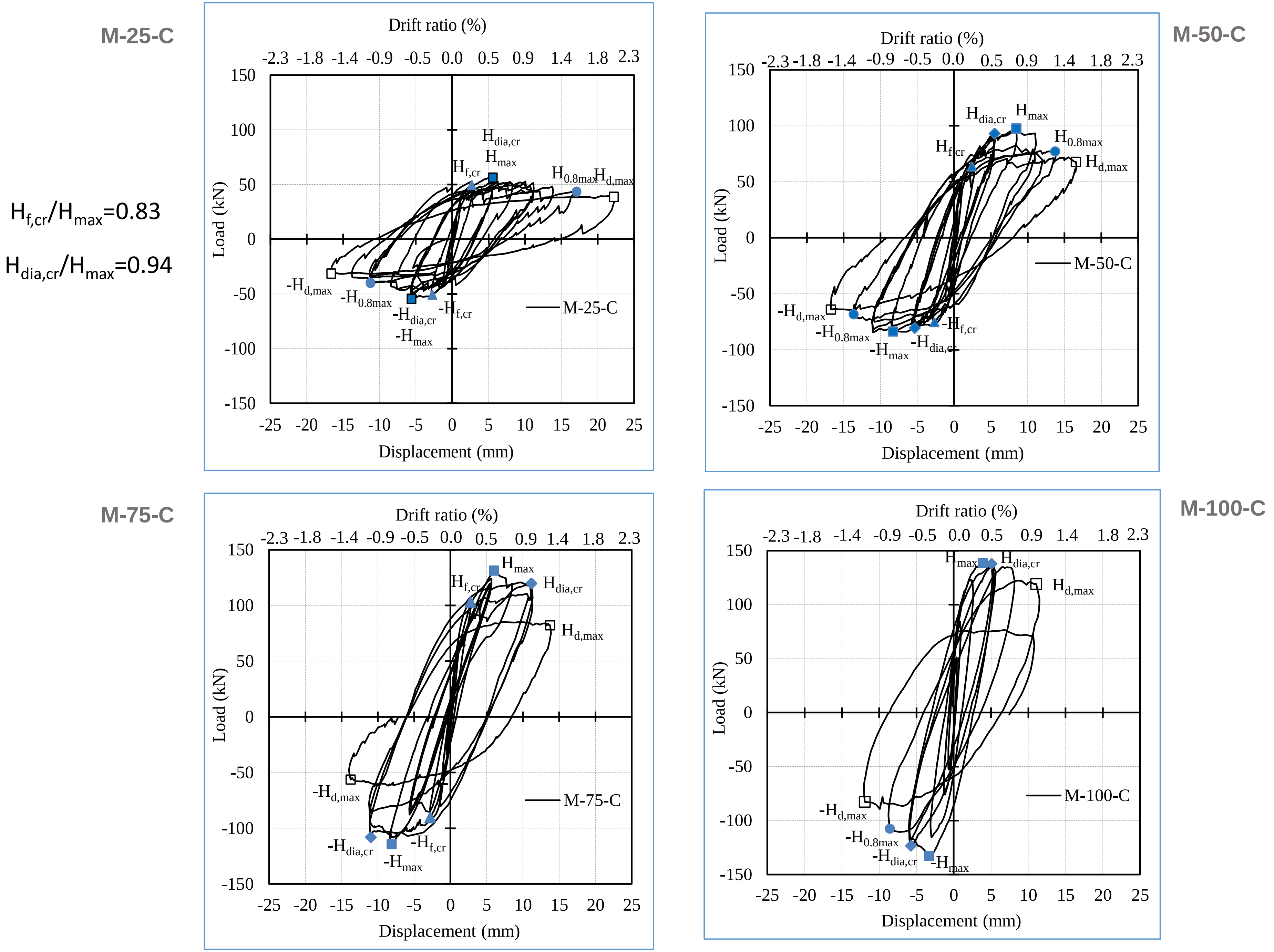
M-75-C



M-100-C

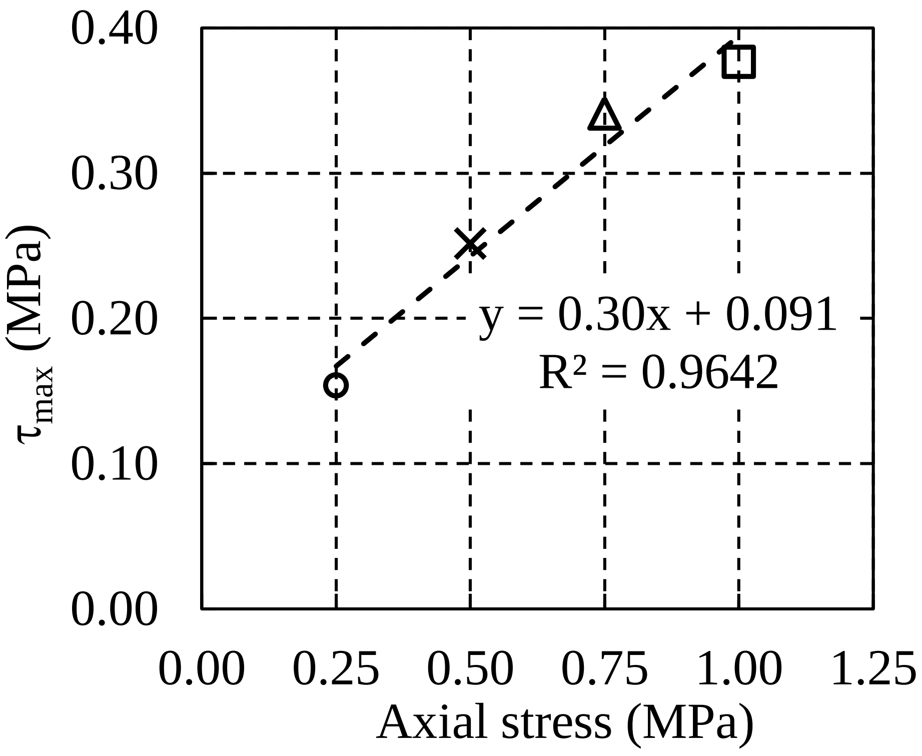


Specimen	Failure mode
M-25-C	Shear (Flexure+++)
M-50-C	Shear (Flexure++)
M-75-C	Shear (Flexure+)
M-100-C	Shear



M-25-C
M-50-C
M-75-C
M-100-C
Hf,cr/Hmax=0.83
Hdia,cr/Hmax=0.94
Drift ratio (%)
Load (kN)
Displacement (mm)
Hdia,cr
Hmax
Hf,cr
H0.8max
Hd,max
-Hd,max
-H0.8max
-Hdia,cr
-Hmax
-Hf,cr
M-25-C
M-50-C
M-75-C
M-100-C

Shear strength vs. pre-compression stress

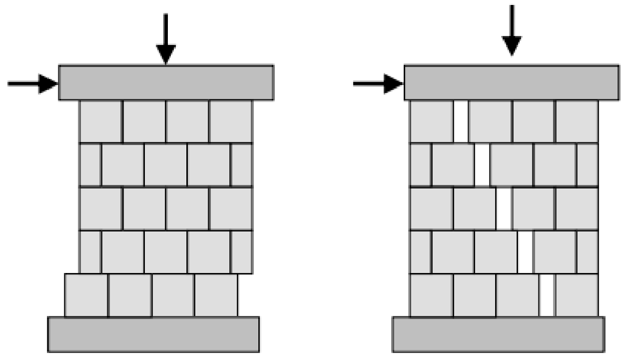


$$\tau_{em} = \tau_o + \mu\sigma$$

Global friction coefficients

TDY (2007): 0.5

EC6 (1996), NTC08: 0.4



Intervention

Intervention-Rules of Thumb (ISCARSAH, 2003)

- The best therapy is preventive maintenance
- No actions should be undertaken without demonstrating that they are indispensable.
- Keep intervention to the minimum to guarantee safety and durability with the least harm to heritage values.
- Deal with the cause of the problem, not only the results!

Intervention-Rules of Thumb (ISCARSAH, 2003)

- The choice between “traditional” and “innovative” techniques should be weighed up on a case-by-case basis and give preference to those that are least invasive and most compatible with heritage values, bearing in mind safety and durability requirements.
- At times the difficulty of evaluating the real safety levels and the possible benefits of interventions: incremental approach, starting from a minimum level of intervention, with the possible subsequent adoption of a series of supplementary or corrective measures.
- Where possible, any measures adopted should be “reversible” so that they can be removed and replaced with more suitable measures when new knowledge is acquired.

Intervention-Rules of Thumb (ISCARSAH, 2003)

- The characteristics of materials used in restoration work (in particular new materials) and their compatibility with existing materials should be fully established. This must include long-term impacts, so that undesirable side effects are avoided.
- The distinguishing qualities of the structure and its environment, in their original or earlier states, should not be destroyed.
- Each intervention should, as far as possible, respect the concept, techniques and historical value of the original or earlier states of the structure and leaves evidence that can be recognised in the future.
- Intervention should be the result of an overall integrated plan that gives due weight to the different aspects of architecture, structure, installations and functionality.
- The removal or alteration of any historic material or distinctive architectural features should be avoided whenever possible.

Intervention-Rules of Thumb (ISCARSAH, 2003)

- Deteriorated structures whenever possible should be repaired rather than replaced.
- Imperfections and alterations, when they have become part of the history of the structure, should be maintained so far so they do not compromise the safety requirements.
- Dismantling and reassembly should only be undertaken as an optional when conservation by other means impossible, or harmful.

Intervention-Rules of Thumb (ISCARSAH, 2003)

- Any proposal for intervention must be accompanied by a programme of control to be carried out, as far as possible, while the work is in progress.
- Measures that are impossible to control during execution should not be allowed.
- Checks and monitoring during and after the intervention should be carried out to check the efficacy of the results.
- All the activities of checking and monitoring should be documented and kept as part of the history of the structure.

Intervention Scales

Minor

- Repair or renewal of damaged façade elements, wall coverings, plasters etc. of historical or monumental structures
- Using as much as possible their original materials, respecting original forms and colors. Interventions within this context must follow the original design and not make any changes that may affect the plan and appearance of the building.

Major

Includes consolidation, strengthening, reconstruction, reintegration, renovation and moving.

Such as interventions for;

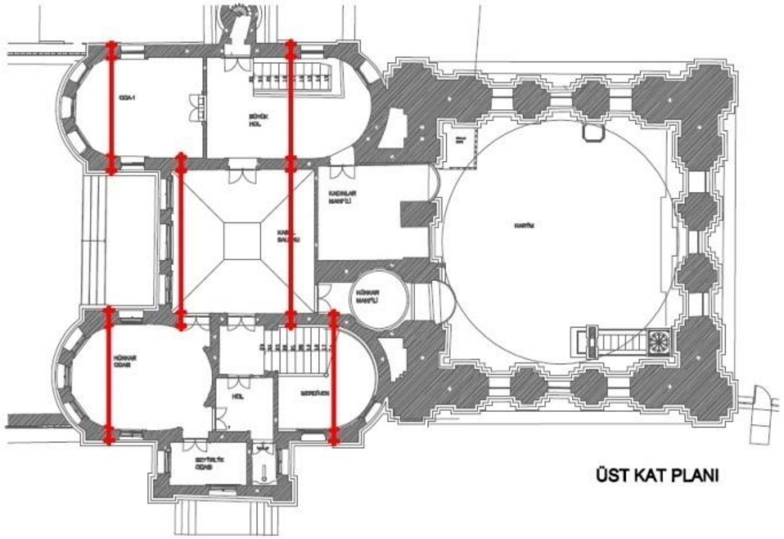
- Enhancing the structural integrity
- Enhacing elements such as domes, vaults and arches
- Enhancing the wall behavior
- Pillars and columns
- Foundations and soil
- Non-structural elements

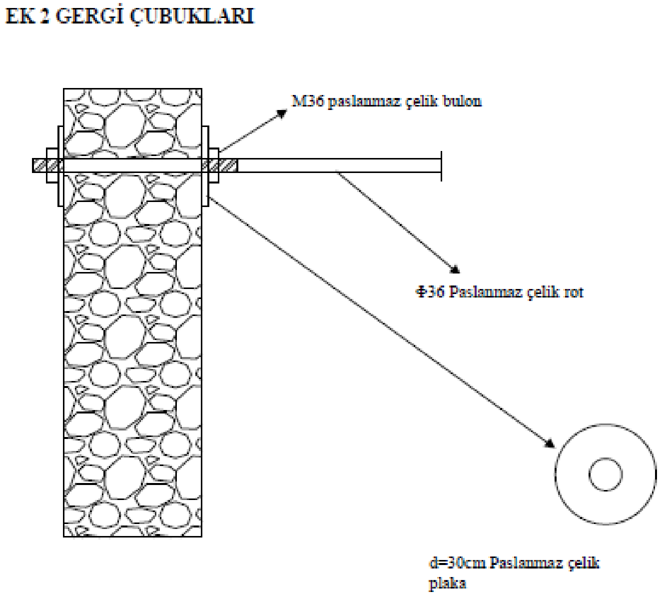
Use of antiseismic devices

Intervention Examples

1. Enhancing the structural integrity

- Addition of steel ties



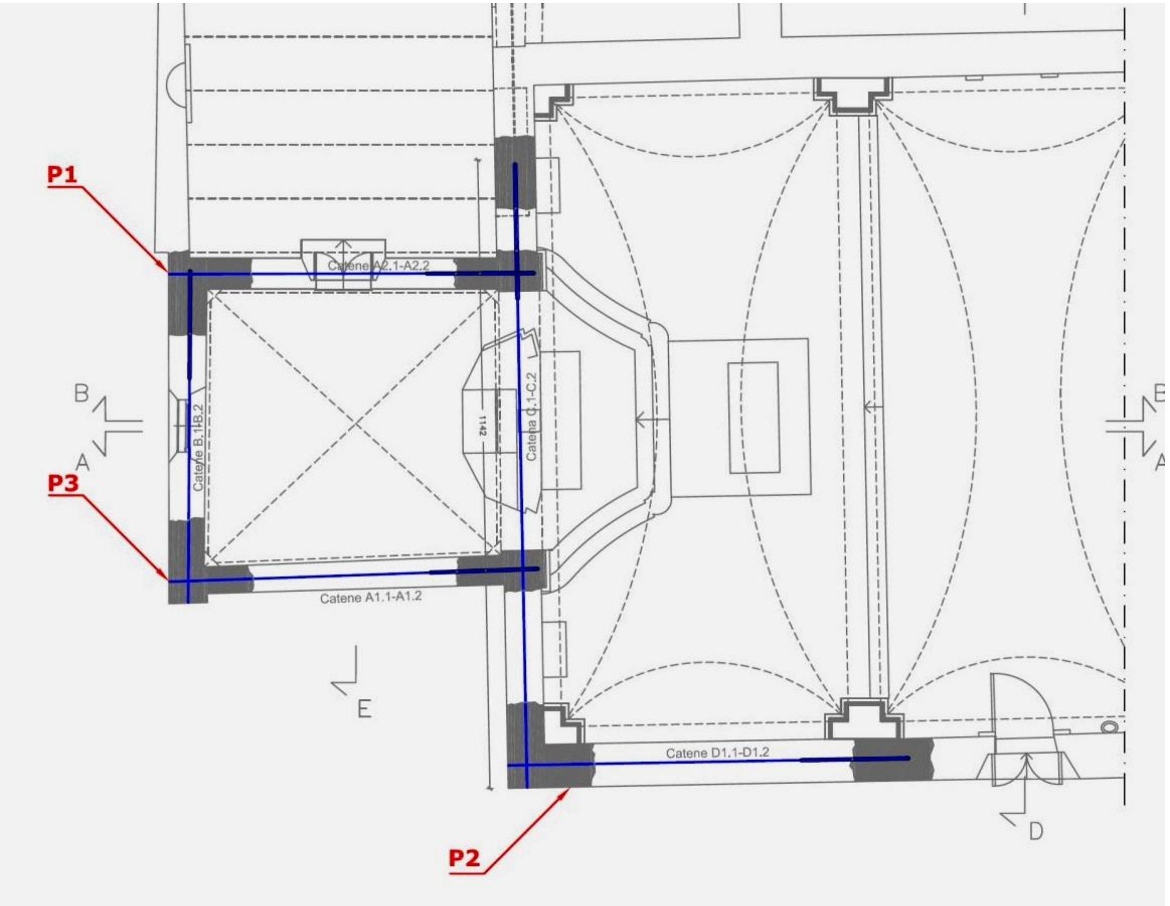


Küçük Mecidiye Camii, İstanbul

Intervention Examples

1. Enhancing the structural integrity

- Addition of steel ties



Şeyh Süleyman Mescidi
(Source: Dr. Olcay Aydemir)

Intervention Examples

1. Enhancing the structural integrity

- Addition of belts

Metal or FRP strips can be used for improving the box behavior

Post-tensioning of the belts is posiible

(Source: Niker EU Project-D3.2)

Intervention Examples

1. Enhancing the structural integrity

- Reconstruction of the joints of discrete intersecting walls

Gökmedrese, Sivas

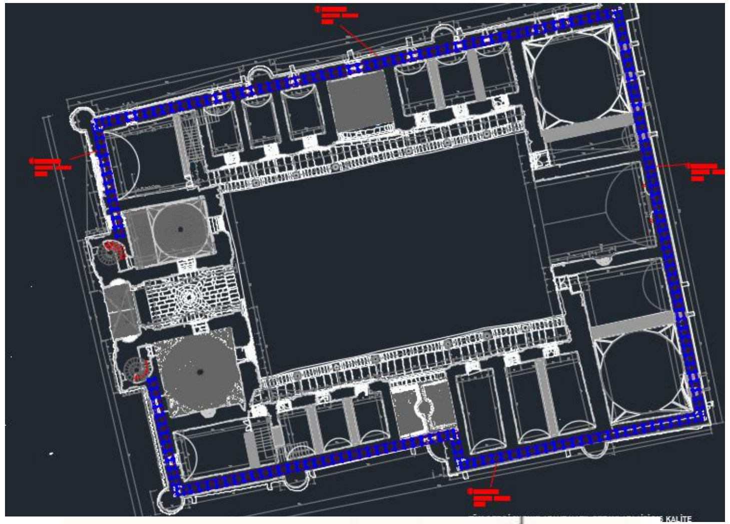
Önce

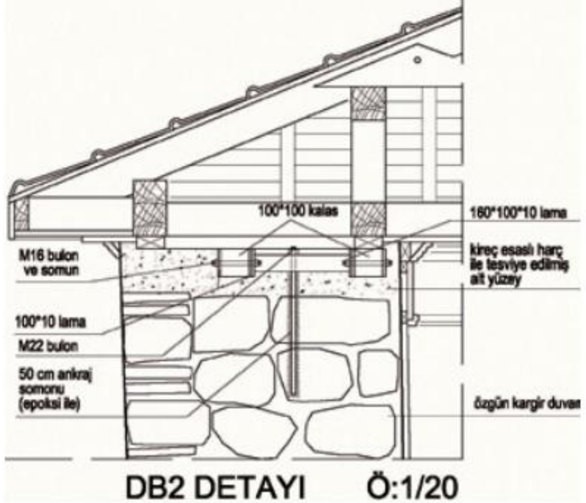
Çürütülüp yeniden oluşturulan dik duvar birleşimi

Intervention Examples

1. Enhancing the structural integrity

- Addition of lintels over the walls





Intervention Examples

1. Enhancing the structural integrity

- Replacement of decayed timber or metal members of main walls

(Kaynak: Dr. Olcay Aydemir)

Intervention Examples

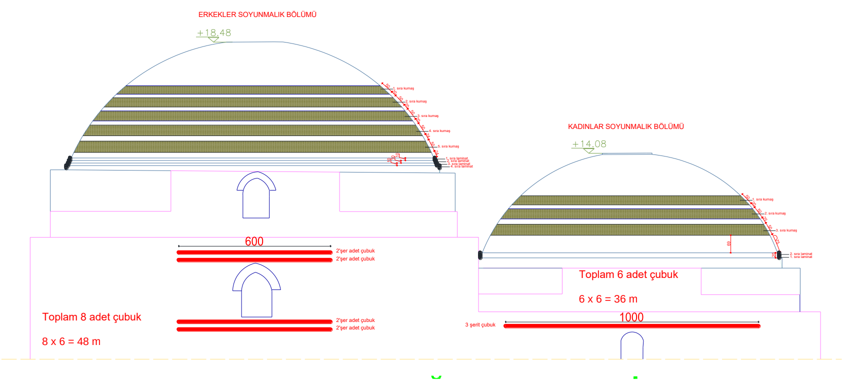
2. Enhancement of Roof Elements

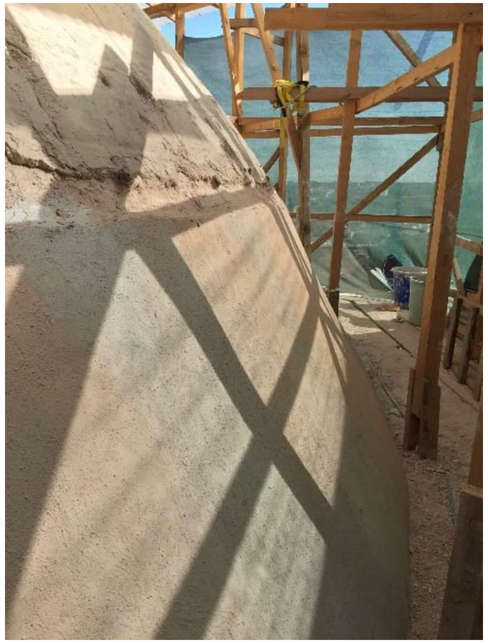
•Use of steel ties for resisting lateral thrust

Intervention Examples

2. Enhancement of Roof Elements

- Addition of FRP tension ring around the base of a dome





Intervention Examples

2. Enhancement of Roof Elements

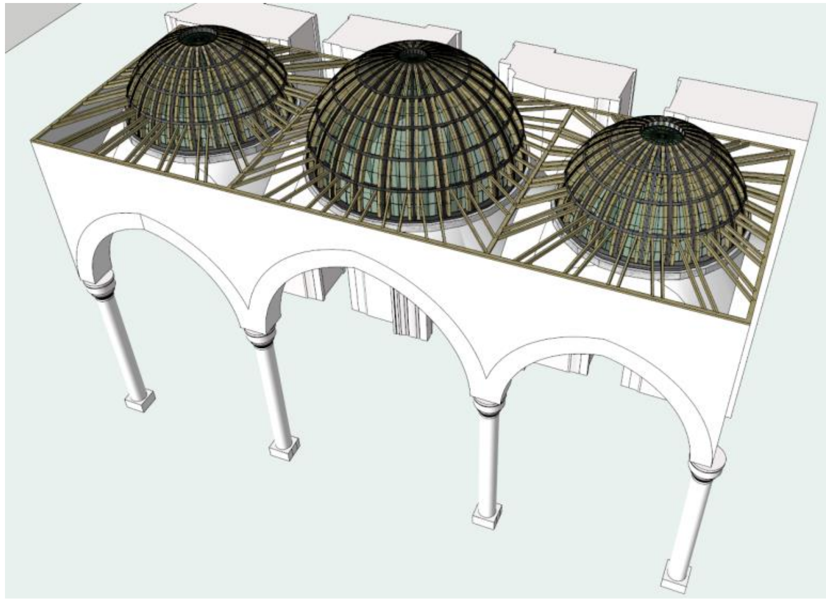
- Addition of steel tension ring around the base of a dome

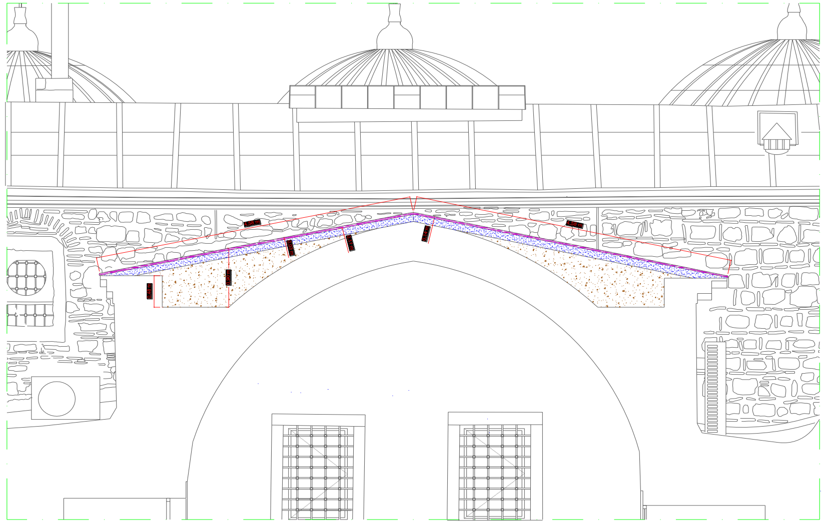
Kütahya Kurşunlu Camii (Kaynak: İnş.Yük.Müh. Fikret Kuran)

Intervention Examples

2. Enhancement of Roof Elements

- Removal of overweight
- Be careful, sometimes some load is good for walls.





Intervention Examples

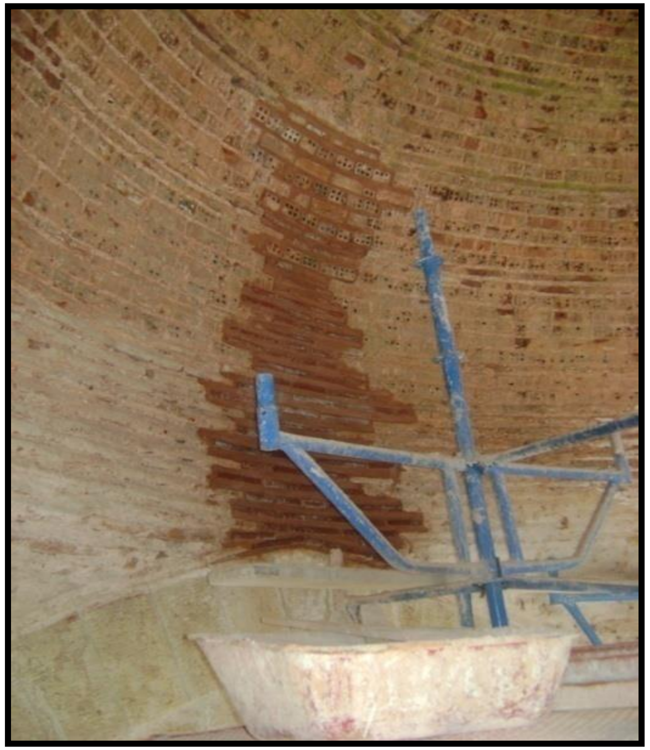
3. Enhancing the wall behavior

- Local repairs of existing cracks, deterriorations, deformations, material losses (local reconstruction, repointing)
- The repair materials should be chemically, physically and mechanically compatible with the original ones

Intervention Examples

3. Enhancing the wall behavior

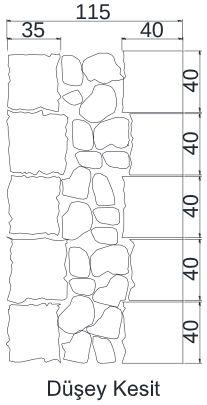
- Local reconstruction

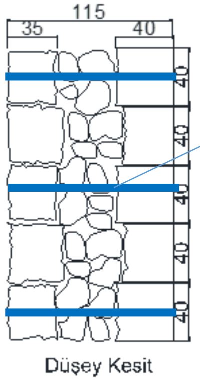


Intervention Examples

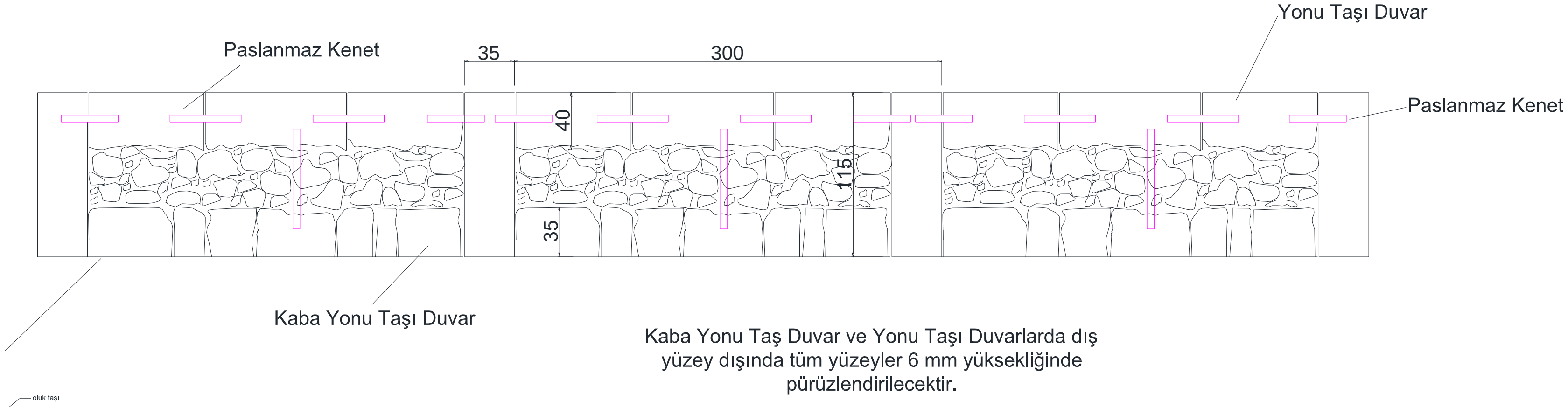
3. Enhancing the wall behavior

- Transverse tying the wall leaves





Steel or FRP ties



Intervention Examples

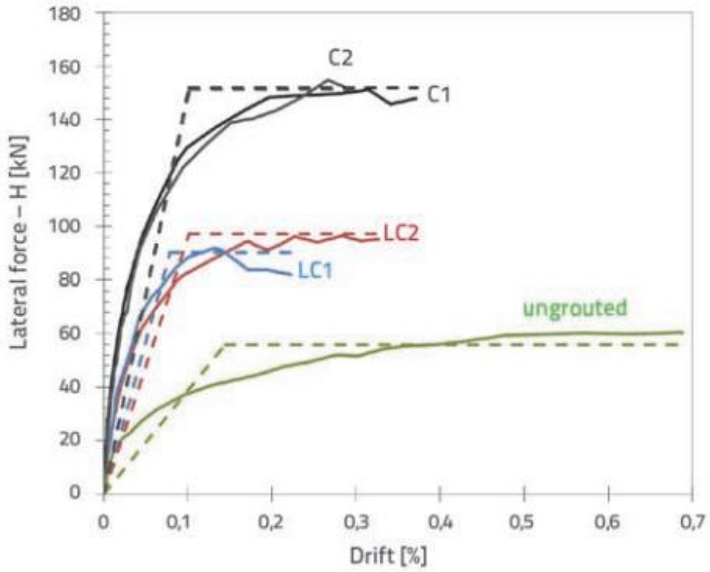
3. Enhancing the wall behavior

• Grout Injection

Filling of voids with non-cement grout injection

Low pressure

(Source: İnş.Yük.Müh. Fikret Kuran)



Uranjek et al. (2014)

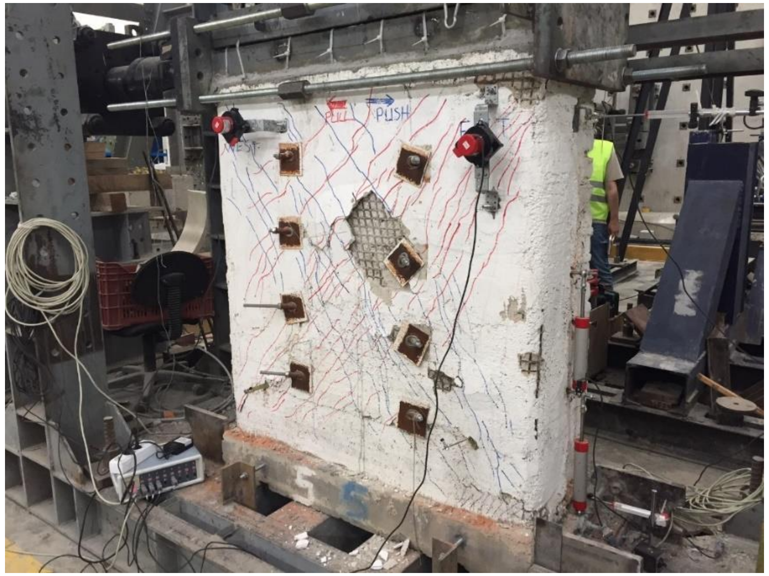
Intervention Examples

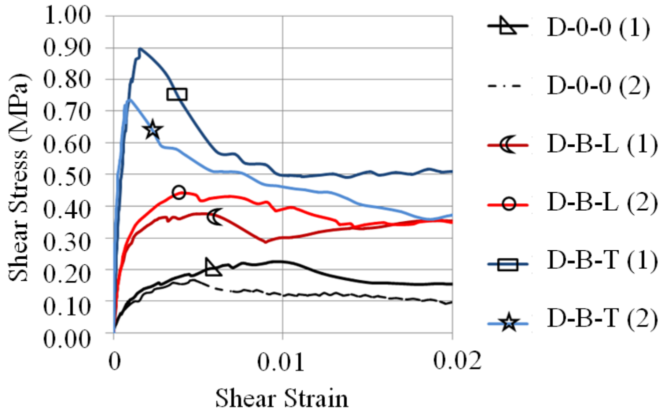
3. Enhancing the wall behavior

- Reinforced Plaster application

FRP composite or stainless steel mesh can be used as reinforcement

TRM reinforced Wall tests at ITU

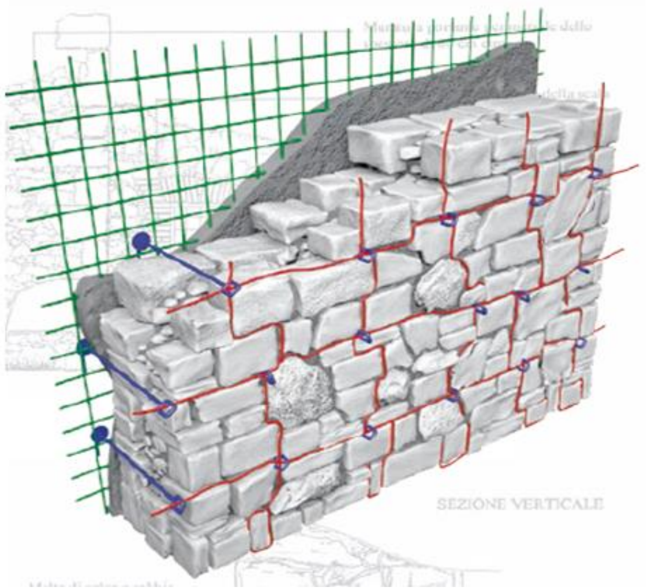




Intervention Examples

3. Enhancing the wall behavior

- Reinforced Repointing



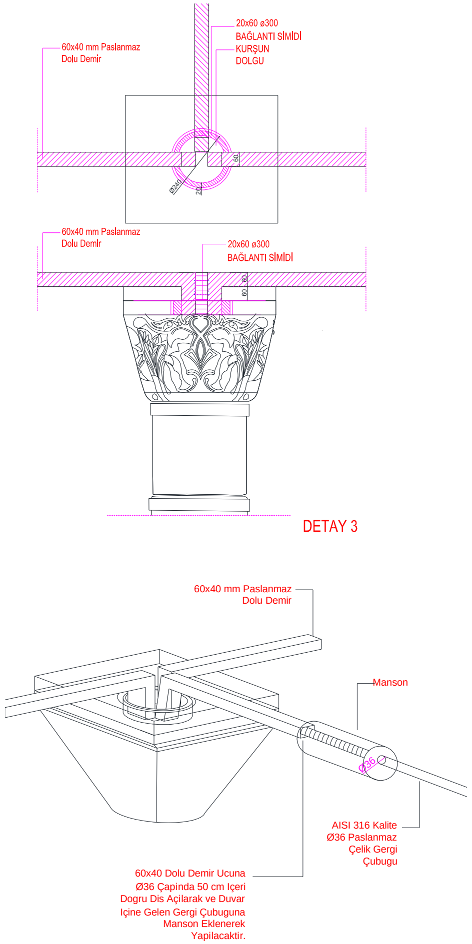
Steel wires

(Source: Dr. Olcay Aydemir)

FRP reinforcement

Intervention Examples

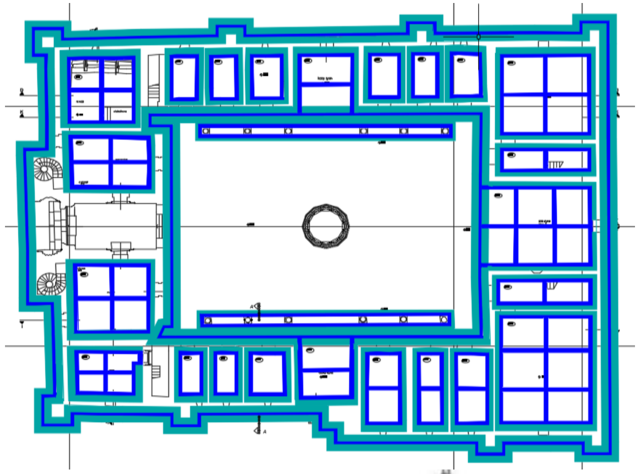
4. Pillars and columns

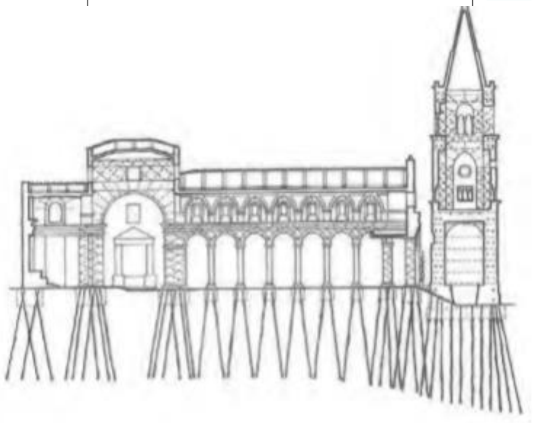


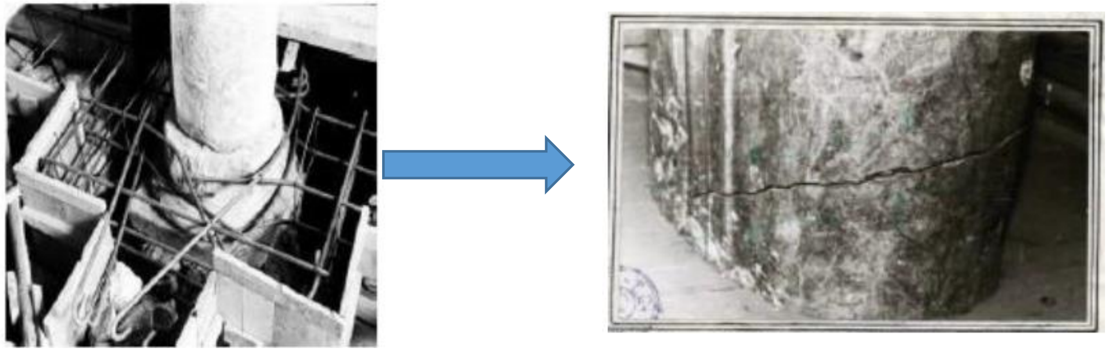
Intervention Examples

5. Interventions to soil and foundations

Foundation enlargement, insertion of piles, the use of soil improvement techniques, water drainage





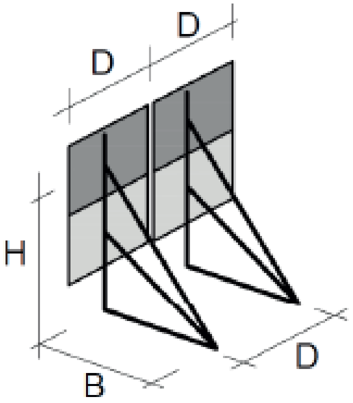


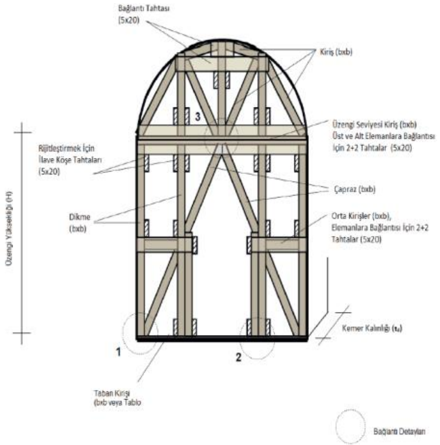
Be careful!

Source: Fikret Kuran

Emergency Intervention

- Before disaster: Risk evaluation, mitigation, and preparedness,
- During disaster: Emergency response,
- After disaster: Damage assessment, immediate intervention, and rehabilitation.





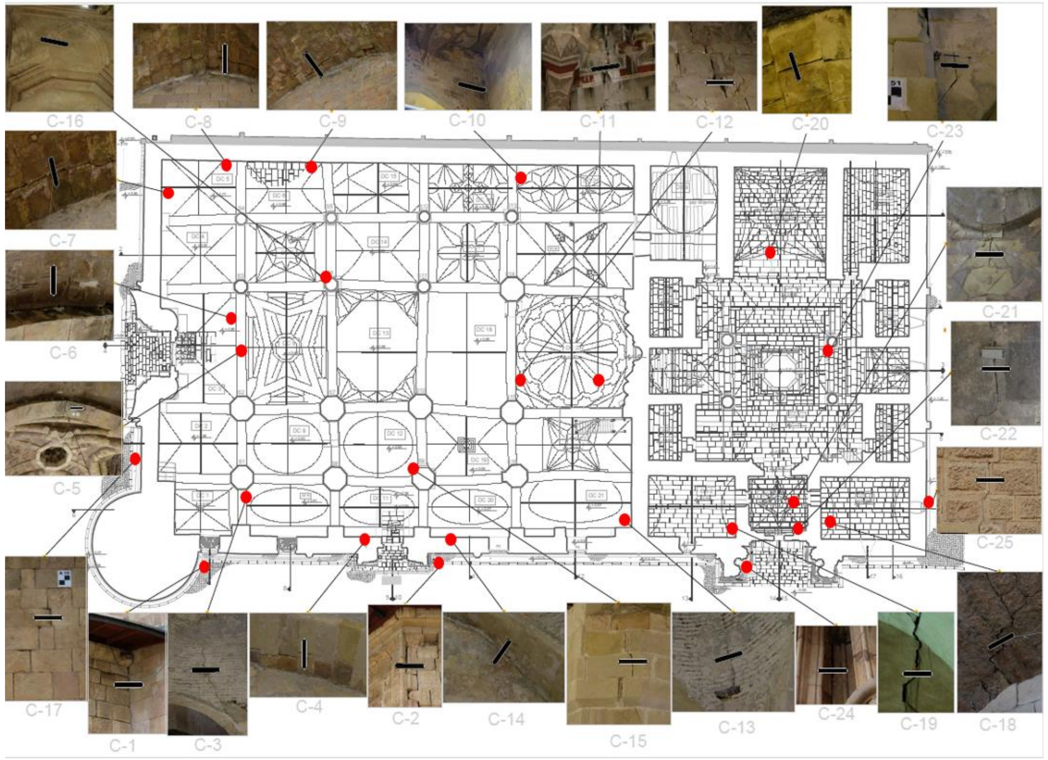
Monitoring

Interval or continuous monitoring of the structure before and after the interventions

Model updating

Gives clue about the weakness

Gives clue about the efficacy of the intervention



Conclusions

In the case of structural assessment and interventions for historic structures:

- There is no magical wand!
- Highly multi-disciplinary approach is required
- Extensive planning is required, not only for today, but also for future
- Side-effects should be considered
- Come backs from wrong interventions always leave traces
- Monitoring before and after an intervention is a good way of control
- Proper diagnosis is a must for a proper treatment.

Thank You...