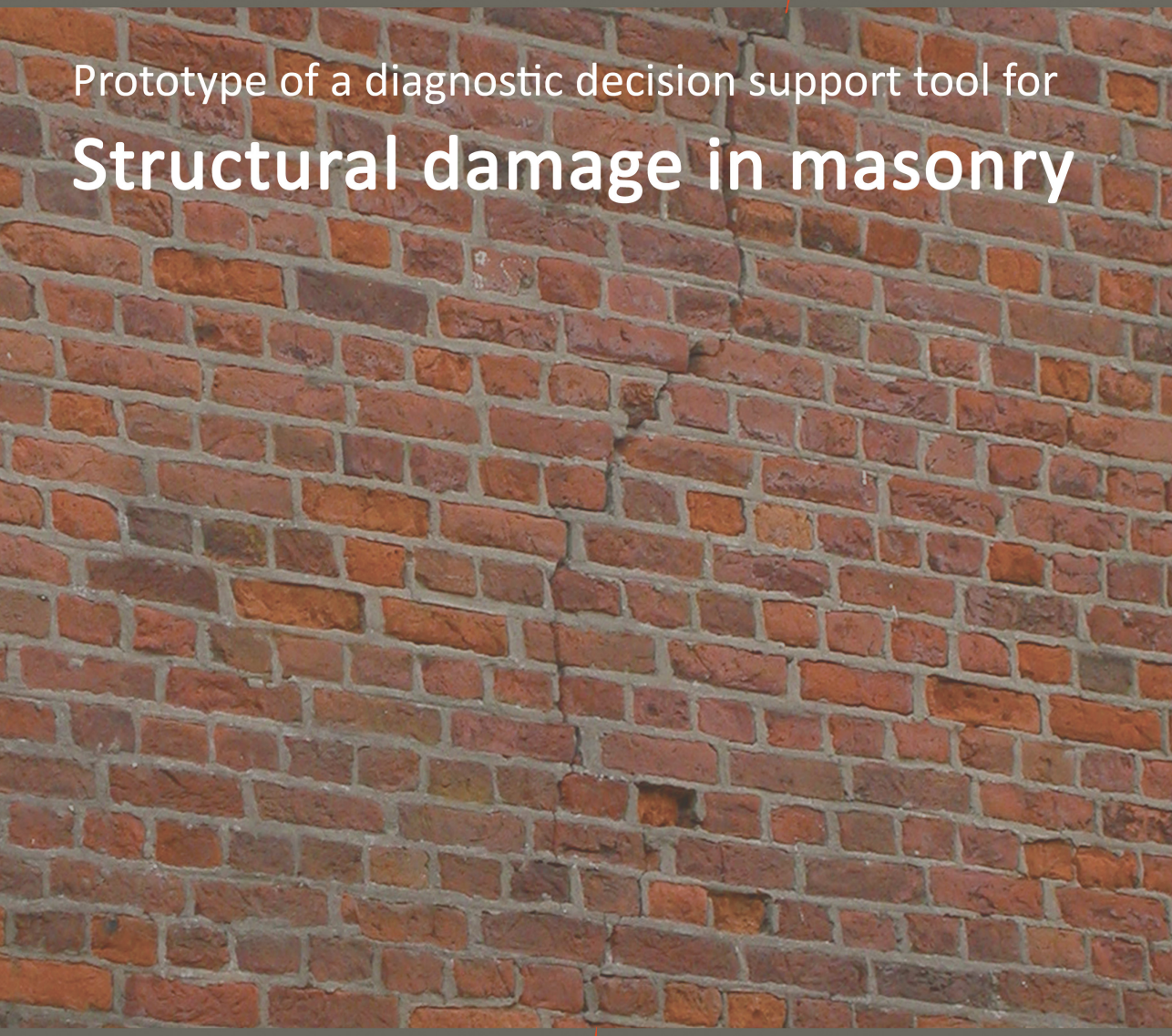
Prototype of a diagnostic decision support tool for

Structural damage in masonry



Ilse de Vent

Prototype of a diagnostic decision support tool for

Structural damage in masonry

Ilse Anne Elisabeth DE VENT

Prototype of a diagnostic decision support tool for structural damage in masonry
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Disclaimer

This prototype of a diagnostic decision support tool has been developed within the framework of a PhD research project on the diagnosis of structural damage in traditional (loadbearing, solid, unreinforced) masonry, conducted at Delft University of Technology. It combines and structures diagnostic expert knowledge deduced from over 500 damage cases selected from literature. While the main focus of the project has been on the Netherlands, and specific attention has been paid to historical buildings, the results are expected to allow use in a broader context. For background information about the development of this tool and the terminology used here, please refer to the PhD thesis [de Vent 2011].

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Notation

Symbol	Designation
E	Environmental context condition
G	Geometrical context condition
M	Material context condition
S	Symptom
T	Time context condition
☐	Hypothesis
■	Essential condition, the presence of which allows the cause in question to occur. Absence of this condition implies that the cause in question is not applicable to the damage under investigation.
·	Condition is not relevant for the cause in question.
①-⑨	Equivalent essential conditions, the presence of at least one of which allows the cause in question to occur. Absence of all these conditions implies that the cause in question is not applicable to the damage under investigation.

Introduction

This diagnostic decision support tool has been designed to facilitate the diagnosis of structural damage in masonry. It intends to offer support in the interpretation of symptoms and context of a damage. To do this, the tool introduces 60 damage patterns, identified by their essential characteristics and each linked to its possible causes. As an easy-reference manual, the tool provides insight into the occurrence of structural damage in masonry, offers alternative explanations, and helps to reach a sound, well-founded hypothesis.

To use this diagnostic decision support tool, you pass through four steps:
1. Determine the damage pattern via the decision tree;
2. Confirm that the damage pattern indeed matches your case;
3. Study the hypotheses belonging to the damage pattern; and
4. Examine the essential conditions to confirm or refute hypotheses.

These four steps are explained below.

1. Determine the damage pattern

The first step in using this diagnostic tool is to determine which of the 60 structural damage patterns corresponds best with the damage you are investigating. This is done through the help of a decision tree, which can be found in **Part I** of this book. Starting at A each column of the tree presents a statement on the appearance of the damage. Carefully

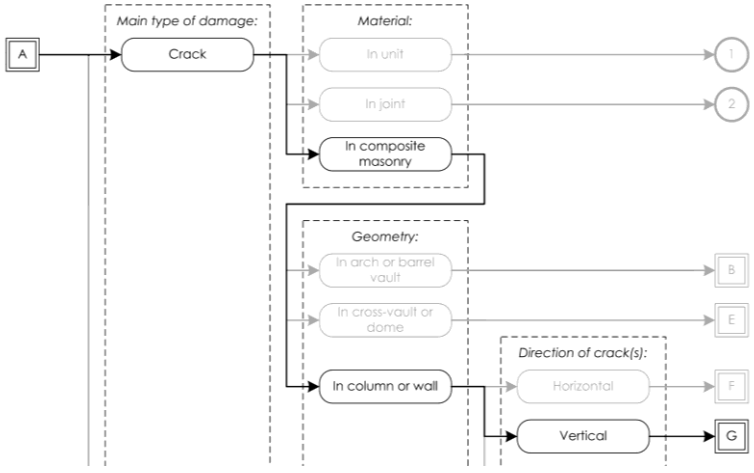


Illustration of Part I: determining the relevant damage pattern, e.g. for a wall with a vertical crack.

read all options that are contained within the dashed rectangle, and choose the one that best suits the damage you have under investigation. Then, following the arrow linked to this option, you proceed with the next statement in the second column, and again choose the most suitable option.

Arriving at the right hand side of the tree, you will find either a number in a circle (e.g. ⑥) or a letter in a square (e.g. G). The number refers you directly to the corresponding damage pattern in Part II of the book. The letter points to a subsequent part of the decision tree in Part I, with which you should proceed until you reach a number; then, turn to the description of the corresponding pattern in Part II.

If the damage under investigation does not seem to fit in one of the categories presented, limit your focus to a smaller area and try to determine the damage pattern part by part. Complete the next steps 2 to 4 for each of these options. Then, check for overlapping hypotheses that could explain all observed damage characteristics.

2. Confirm that the damage pattern indeed matches your case

When the damage pattern has been determined, you can turn to **Part II** of this tool. There, you will find the 60 damage patterns in sequence of number. For each of the patterns, the following information is presented:

A. Damage pattern
B. Hypotheses
C. Essential conditions
D. Further reading

Always start with the illustration, the list of characteristics and the examples from practice that you find below **A. Damage pattern**. Compare them with the damage you have

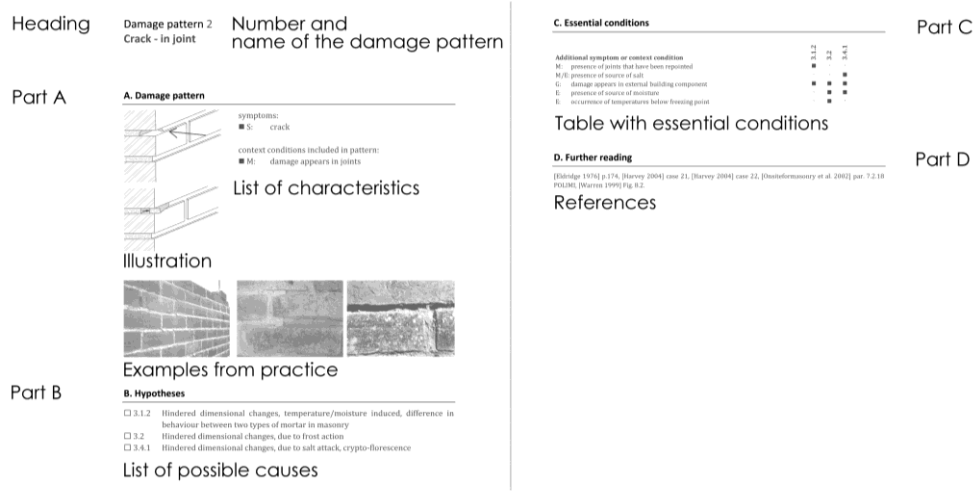


Illustration of Part II: information on damage patterns.

under investigation and check whether the damage pattern indeed matches your case. If so, you can proceed with the next step. If not, please return to the decision tree in Part I.

3. Study the hypotheses belonging to the damage pattern

Below **B. Hypotheses** you will find a list of causes that can underlie the damage pattern in question. These are the hypotheses that may apply to your case. Study these hypotheses carefully, keeping in mind that the order in which they are listed does not pronounce upon their probability. The arrows drawn in the illustration of the damage pattern below A. Damage pattern may help to appreciate the forces generated by the different processes. Then, proceed with the next step.

4. Examine the essential conditions to confirm or refute hypotheses

For each damage pattern, below **C. Essential conditions** tables are drawn up which inform about the conditions that are essential for the occurrence of each hypothesis. Verify whether these conditions may apply to the damage you have under investigation. If the possibility of one condition can be excluded, the corresponding cause can be removed from the list of hypotheses for your case. On the other hand, when all conditions related to a certain hypothesis are present, this indicates that this cause should be taken into account in further investigations.

For settlements, the essential conditions are the same for all associated damage patterns. Therefore, these conditions have been brought together in **Part III** of the tool. The table works in the same way as the ones presented for the separate damage patterns. However, some hypotheses have equivalent conditions, the presence of at least one of which is sufficient to allow the cause in question to occur. These conditions are marked with a number.

Illustration of Part III: hypotheses for vertical and horizontal settlement.

Please bear in mind that following above four steps will not lead you to an instant, cut-and-dried diagnosis. This tool has been designed to give you an overview of alternative explanations, to help you decide which hypothesis is the most likely cause of the damage you are investigating.

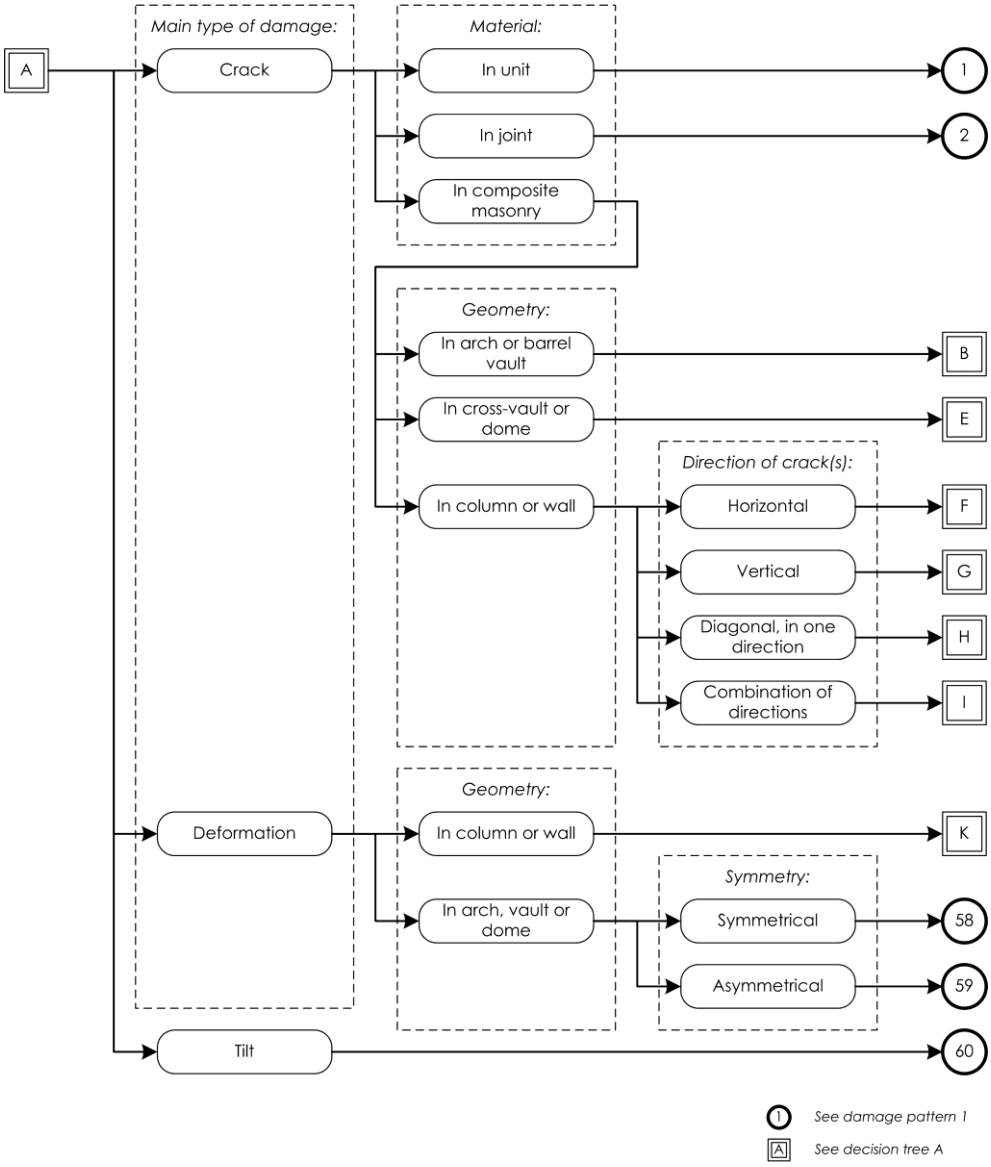
Furthermore, this diagnostic decision support tool has been developed with a view to the Dutch situation. However, it is expected to be of profitable use in other countries as well.

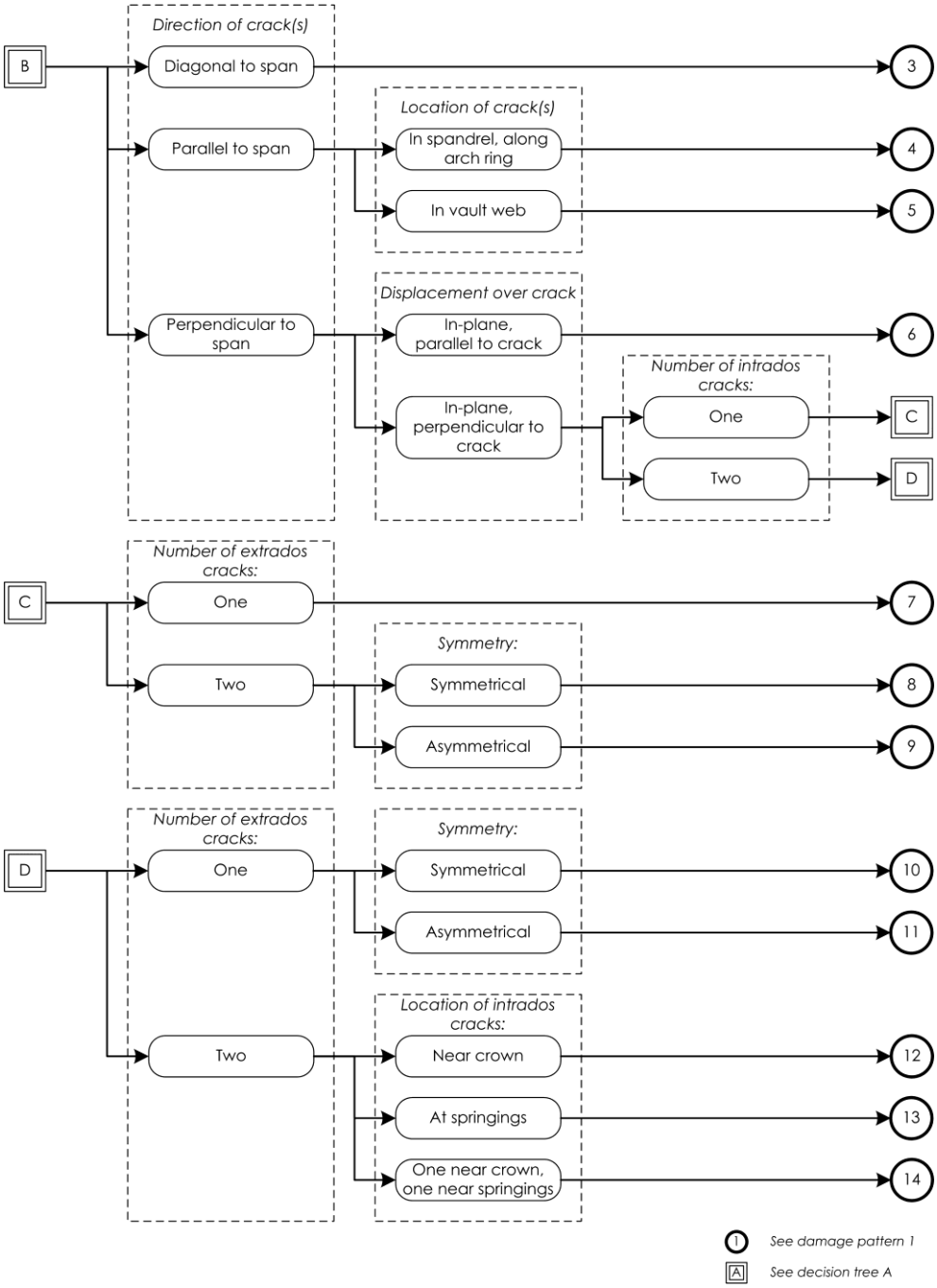
Please note that this tool is designed for damage in masonry. If the damage in question appears in plasterwork, you should, thus, ascertain whether or not it continues in the underlying masonry. This may imply the removal of a small area of plasterwork.

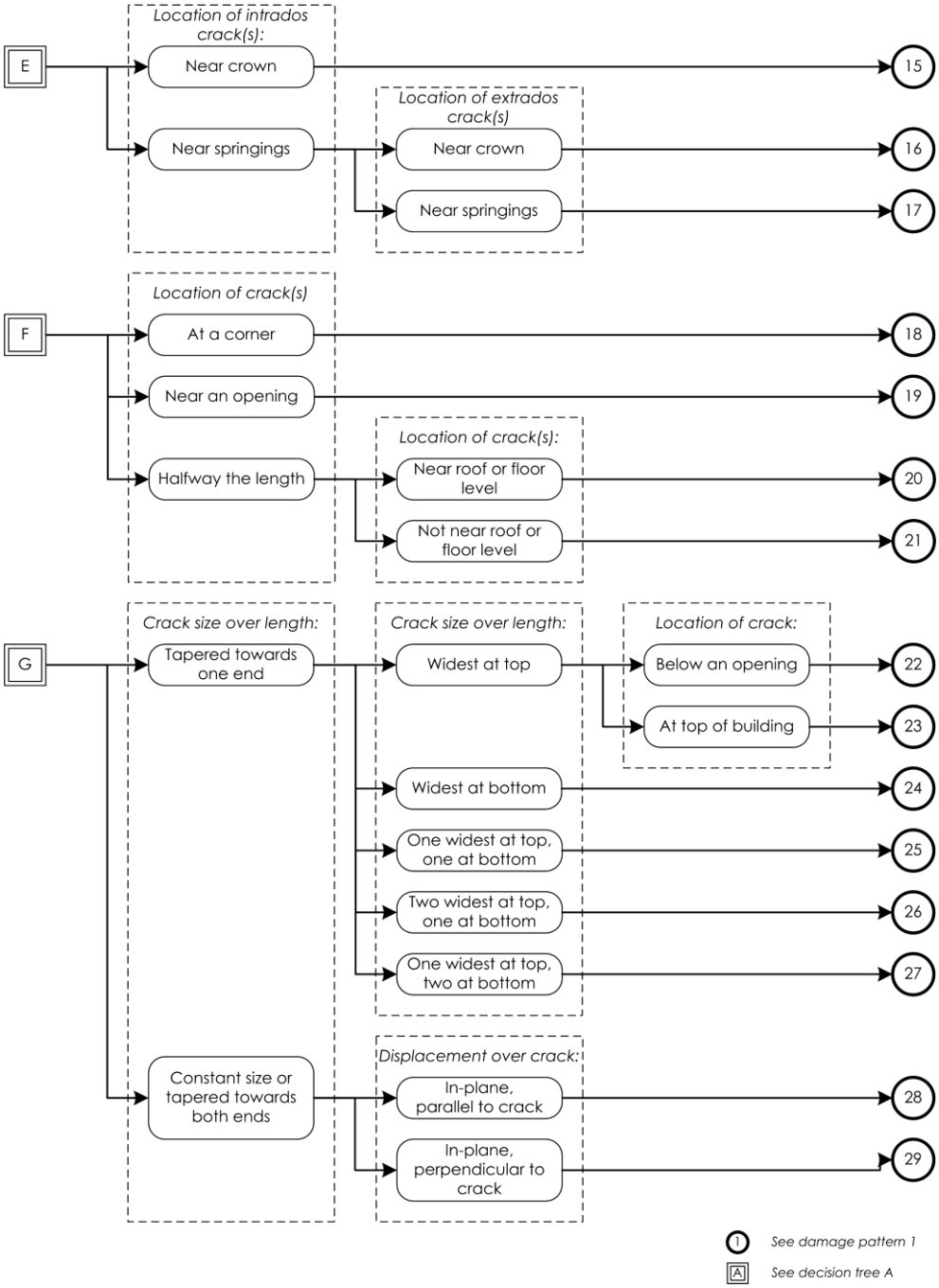
For each pattern, below **D. Further reading**, you can find references to books and articles which include discussions of this damage pattern. In fact, these are the sources on which this diagnostic tool has been based.

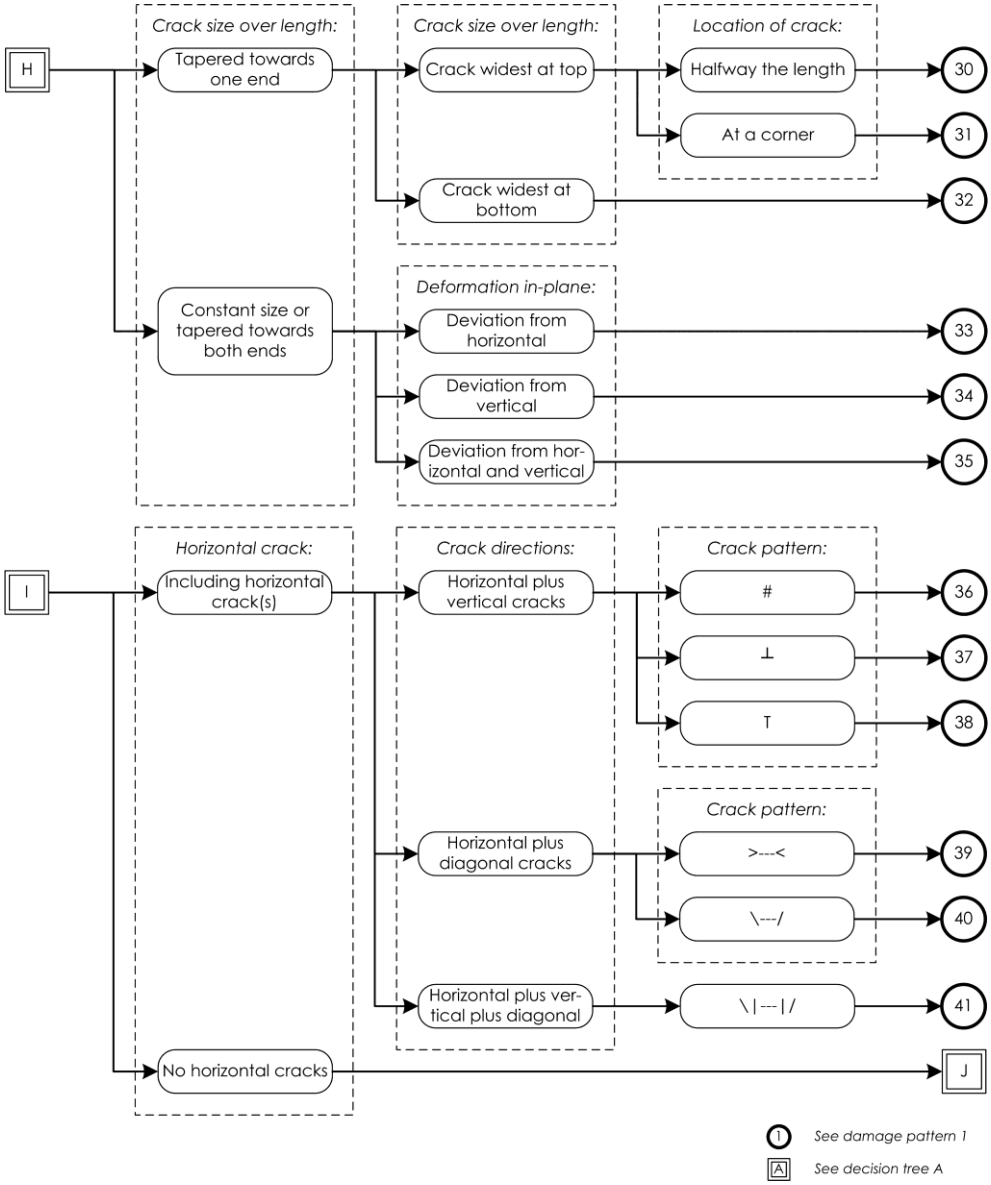
Part I

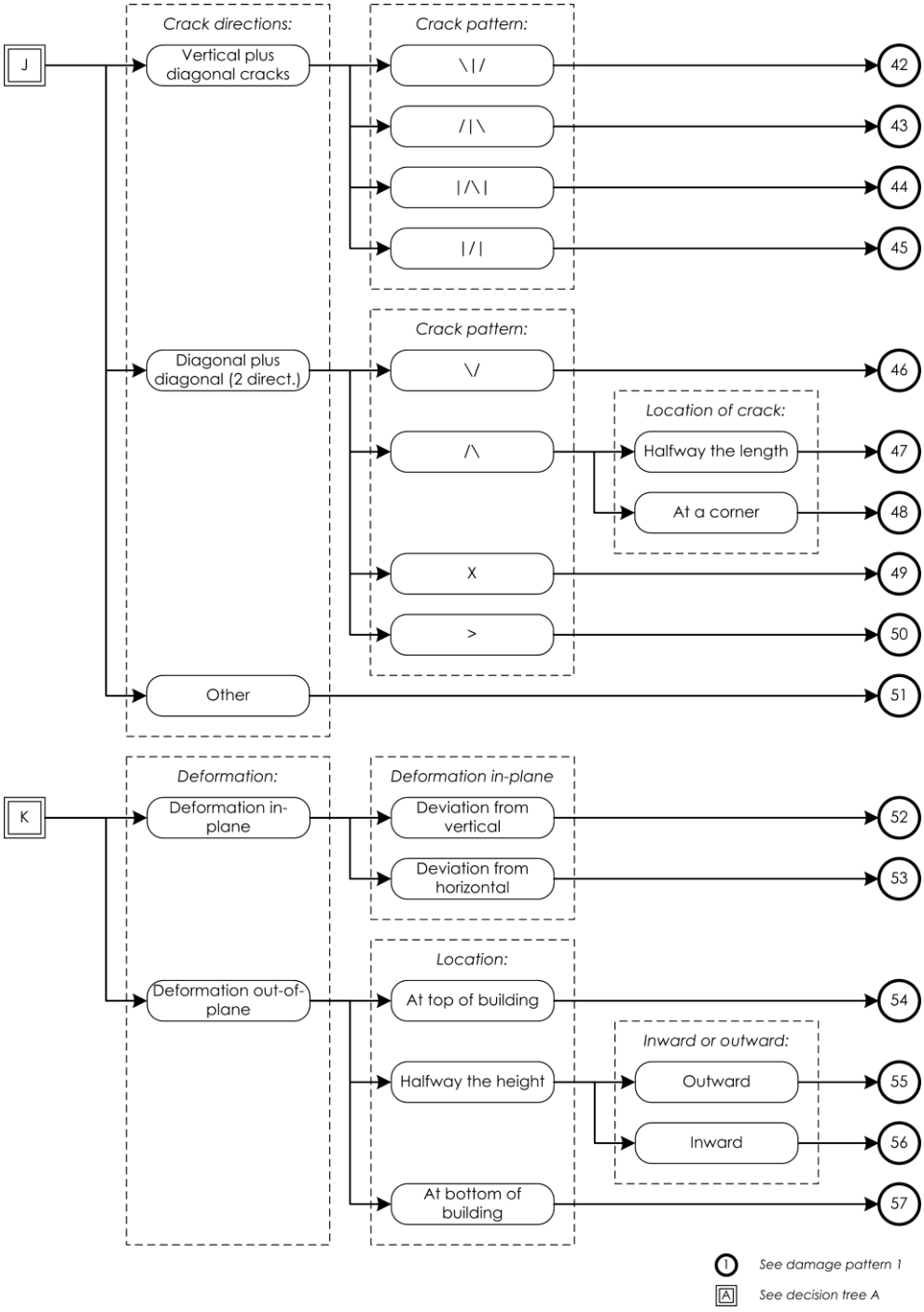
Decision tree


A
Main type of damage:
Crack
Material:
In unit
1
In joint
2
In composite masonry
Geometry:
In arch or barrel vault
B
In cross-vault or dome
E
Direction of crack(s):
In column or wall
Horizontal
F
Vertical
G
Diagonal, in one direction
H
Combination of directions
I
Geometry:
Deformation
In column or wall
K
Symmetry:
In arch, vault or dome
Symmetrical
58
Asymmetrical
59
Tilt
60
See damage pattern 1
See decision tree A


B
Direction of crack(s)
Diagonal to span
3
Parallel to span
Location of crack(s)
In spandrel, along arch ring
4
In vault web
5
Perpendicular to span
Displacement over crack
In-plane, parallel to crack
6
In-plane, perpendicular to crack
Number of intrados cracks:
One
C
Two
D
C
Number of extrados cracks:
One
7
Two
Symmetry:
Symmetrical
8
Asymmetrical
9
D
Number of extrados cracks:
One
Symmetry:
Symmetrical
10
Asymmetrical
11
Two
Location of intrados cracks:
Near crown
12
At springings
13
One near crown, one near springings
14
See damage pattern 1
See decision tree A

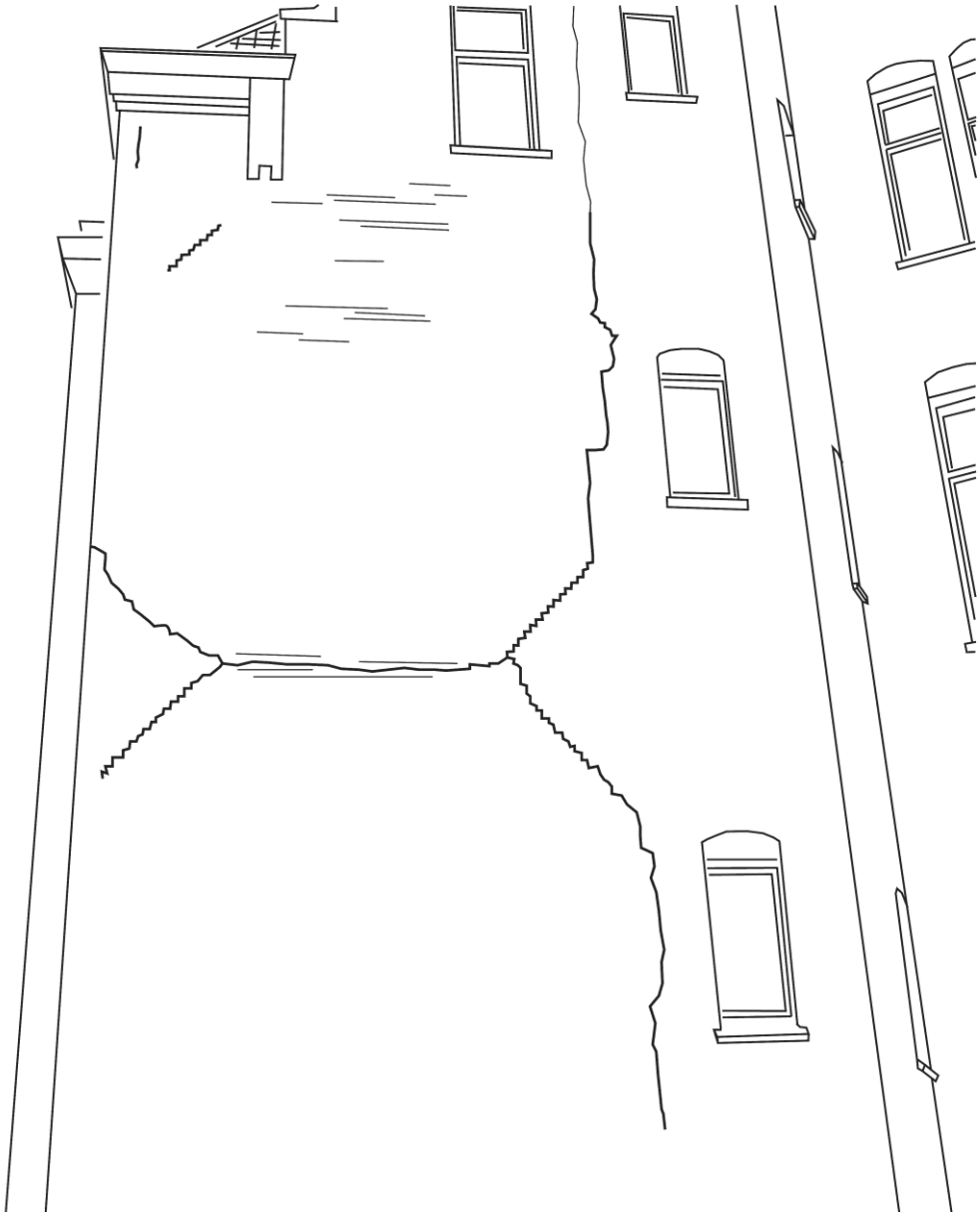

E
Location of intrados crack(s):
Near crown
Near springings
Location of extrados crack(s)
Near crown
Near springings
15
16
17
F
Location of crack(s)
At a corner
Near an opening
Halfway the length
Location of crack(s):
Near roof or floor level
Not near roof or floor level
18
19
20
21
G
Crack size over length:
Tapered towards one end
Constant size or tapered towards both ends
Crack size over length:
Widest at top
Widest at bottom
One widest at top, one at bottom
Two widest at top, one at bottom
One widest at top, two at bottom
Location of crack:
Below an opening
At top of building
22
23
24
25
26
27
Displacement over crack:
In-plane, parallel to crack
In-plane, perpendicular to crack
28
29
See damage pattern 1
See decision tree A


H
Crack size over length:
Tapered towards one end
Crack size over length:
Crack widest at top
Location of crack:
Halfway the length
30
At a corner
31
Crack widest at bottom
32
Constant size or tapered towards both ends
Deformation in-plane:
Deviation from horizontal
33
Deviation from vertical
34
Deviation from horizontal and vertical
35
I
Horizontal crack:
Including horizontal crack(s)
Crack directions:
Horizontal plus vertical cracks
Crack pattern:
#
36
⊥
37
T
38
Horizontal plus diagonal cracks
Crack pattern:
>---<
39
\---/
40
Horizontal plus vertical plus diagonal
\|---|/
41
No horizontal cracks
J
See damage pattern 1
See decision tree A


J
Crack directions:
Vertical plus diagonal cracks
Crack pattern:
\ | /
/ | \
| /\ |
| / |
42
43
44
45
Diagonal plus diagonal (2 direct.)
Crack pattern:
\/
/\
X
>
Location of crack:
Halfway the length
At a corner
46
47
48
49
50
Other
51
K
Deformation:
Deformation in-plane
Deformation out-of-plane
Deformation in-plane
Deviation from vertical
Deviation from horizontal
52
53
Location:
At top of building
Halfway the height
At bottom of building
Inward or outward:
Outward
Inward
54
55
56
57
See damage pattern 1
See decision tree A

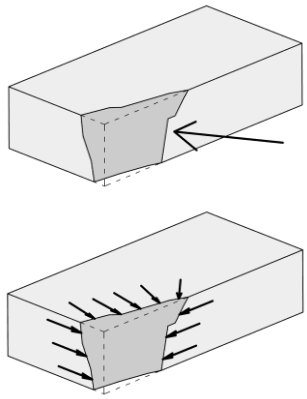
Part II

Damage patterns



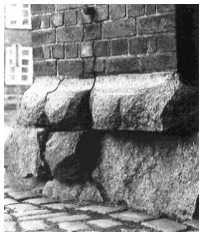
Damage pattern 1
Crack - in unit

A. Damage pattern



symptoms:
■ S: crack

context conditions included in pattern:
■ M: damage appears in units


Examples. [Feilden 2003] Fig. 5.2, [Pieper 1983] Bild 4.1, [Warren 1999] Fig. 8.12.

B. Hypotheses

☐ 2.1.11 Overloading due to change in load, horizontal, impact of object hitting edge
☐ 2.1.14 Overloading due to change in load, horizontal, impact of acts of war
☐ 2.3.3 Overloading due to change in resistance, geometrical discontinuities within dry-jointed masonry
☐ 2.3.4 Overloading due to change in resistance, geometrical discontinuities within stonework worked with hollow bed
☐ 2.3.6 Overloading due to change in resistance, geometrical discontinuities within rubble-core masonry
☐ 2.3.7 Overloading due to change in resistance, geometrical discontinuities in stones not laid on quarry bed

☐ 3.1.2 Hindered dimensional changes, temperature/moisture induced, difference in behaviour between two types of mortar in masonry
☐ 3.1.10 Hindered dimensional changes, temperature/moisture induced, abrupt extreme change in temperature, irreversible swelling in a fire
☐ 3.1.11 Hindered dimensional changes, temperature/moisture induced, lack of flexibility to accommodate movement
☐ 3.2 Hindered dimensional changes, due to frost action
☐ 3.3 Hindered dimensional changes, due to corrosion
☐ 3.4.1 Hindered dimensional changes, due to salt attack, crypto-florescence

C. Essential conditions

Additional symptom or context condition	2.1.11	2.1.14	2.3.3	2.3.4	2.3.6
M: damage appears along the horizontal edges of units	·	·	■	■	■
M: damage appears in dry-jointed masonry	·	·	■	·	·
G: damage appears in external building component	■	·	·	·	·
G: damage appears at protruding edge	■	·	·	·	·
G: damage appears in stones worked with a hollow bed	·	·	·	■	·
G: damage appears in rubble core masonry that has thin shell and high load	·	·	·	·	■
T: damage has appeared after the following occurrence	·	■	·	·	·
E: occurrence of war	·	■	·	·	·

Additional symptom or context condition	2.3.7	3.1.2	3.1.10	3.1.11
S: layering parallel to quarry bed	■	·	·	·
M: damage appears in natural stone	■	·	·	·
M: damage appears only in those stones that were not laid on their quarry bed	■	·	·	·
M: presence of joints that have been repointed	·	■	·	·
G: damage appears in external building component	·	■	·	·
G: absence of sufficient expansion joints	·	·	·	■
T: damage has appeared after the following occurrence	·	·	■	·
E: occurrence of fire	·	·	■	·

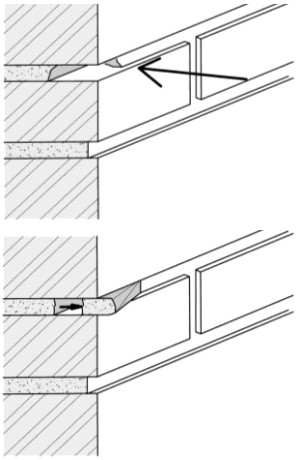
Additional symptom or context condition	3.2	3.3	3.4.1
S: rust stains	·	■	·
M: damage appears at location of iron element	·	■	·
M: presence of iron element embedded in masonry	·	■	·
M/E: presence of source of salt	·	·	■
G: damage appears in external building component	■	·	■
E: presence of source of moisture	■	·	■
E: occurrence of temperatures below freezing point	■	·	·

D. Further reading

[Beckmann and Bowles 2004] fig. 4.4b, [Cook and Hinks 1992] Fig. 8.5, [Croci 1998] Fig. 2.26, [Eldridge 1976] p.169, [Eldridge 1976] p.169, [Douglas and Ransom 2007] Fig. 10.8, [Eldridge 1976] p.177, [Eldridge 1976] p.177, [Eldridge 1976] p.172, [Feilden 2003] Fig. 5.1, [Feilden 2003] Fig. 5.2, [Harris 2001] p.395, [Harvey 2004] case 15, [Harvey 2004] case 20, [Harvey 2004] case 28, [Heyman 1985] Fig. 6, [Hendry and Khalaf 2001] Fig. 7.7, [Loughran 2007] p .31, [Marshall et al. 2009] p. 90 b, c, [Marshall et al. 2009] p. 91 c, d, [Meichsner and Rohr-Suchalla 2008] Bild 218, [Onsiteformasonry et al. 2002] par. 7.2.15 POLIMI, [Onsiteformasonry et al. 2002] par. 7.2.16 POLIMI, [Onsiteformasonry et al. 2002] par. 7.2.21 POLIMI, [Onsiteformasonry et al. 2002] par. 7.4.1 IRMA/IRDI, [Onsiteformasonry et al. 2002] par. 7.5.4 ZAG, [Onsiteformasonry et al. 2002] par. 7.6.6 ZAG, [Onsiteformasonry et al. 2002] par. 7.8.7 GEOCISA, [Pieper 1983] Bild 4.1, [Richardson 2001] plate 1, [Richardson 2001] plate 45, [Warren 1999] Fig. 5.4, [Warren 1999]Fig. 8.1a, [Warren 1999] Fig. 8.1b, [Warren 1999] Fig. 8.3, [Warren 1999] Fig. 8.7, [Warren 1999] Fig. 8.10, [Warren 1999] Fig. 8.12, [Warren 1999] Fig. 10.3, [Watt 2007] p. 108, [Watt 2007] p. 112, [Watt 2007] p. 122.

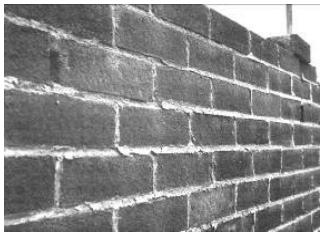
Damage pattern 2
Crack - in joint

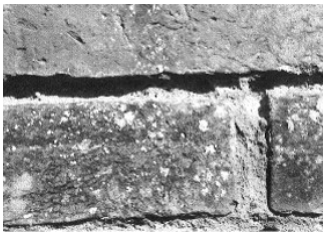
A. Damage pattern



symptoms:
- ■ S: crack

context conditions included in pattern:
- ■ M: damage appears in joints





Examples. [Eldridge 1976] p.174, [Onsiteformasonry et al. 2002] par. 7.2.18 POLIMI, [Warren 1999] Fig. 8.2.

B. Hypotheses

- ☐ 3.1.2 Hindered dimensional changes, temperature/moisture induced, difference in behaviour between two types of mortar in masonry
- ☐ 3.2 Hindered dimensional changes, due to frost action
- ☐ 3.4.1 Hindered dimensional changes, due to salt attack, crypto-florescence

C. Essential conditions

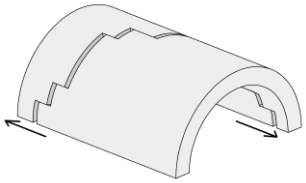
Additional symptom or context condition	3.1.2	3.2	3.4.1
M: presence of joints that have been repointed	■	·	·
M/E: presence of source of salt	·	·	■
G: damage appears in external building component	■	■	■
E: presence of source of moisture	·	■	■
E: occurrence of temperatures below freezing point	·	■	·

D. Further reading

[Eldridge 1976] p.174, [Harvey 2004] case 21, [Harvey 2004] case 22, [Onsiteformasonry et al. 2002] par. 7.2.18 POLIMI, [Warren 1999] Fig. 8.2.

Damage pattern 3
Crack - in arch or barrel vault - diagonal to span

A. Damage pattern



symptoms:
- ■ S: crack
- ■ S: crack direction is diagonal to span
- ■ S: in-plane displacement, perpendicular to crack

context conditions included in pattern:
- ■ G: damage appears in arch or barrel vault

Examples. [Harvey 2004] case 10.

B. Hypotheses

☐ 1.D Horizontal soil movement

C. Essential conditions

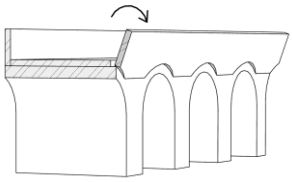
For hypotheses and corresponding essential conditions of horizontal settlement, see Part III of this tool.

D. Further reading

[Harvey 2004] case 10.

Damage pattern 4
Crack - in arch or barrel vault - parallel to span - in spandrel, along arch ring

A. Damage pattern



symptoms:
- ■ S: crack
- ■ S: crack direction is parallel to span
- ■ S: out-of-plane displacement over crack

context conditions included in pattern:
- ■ G: damage appears in arch or barrel vault
- ■ G: damage appears in spandrel wall



Examples. [Harvey 2004] case 25, [Harvey 2004] case 26, [Harvey 2004] case 27.

NB If there is no horizontal out-of-plane displacement over the crack, check for additional cracks perpendicular to the span and use those cracks to determine the pattern; see decision tree B and damage patterns 6 to 14.

B. Hypotheses

- ☐ 2.1.3 Overloading due to change in load, vertical, increase in use load
- ☐ 2.1.8 Overloading due to change in load, horizontal, push of backfill

C. Essential conditions

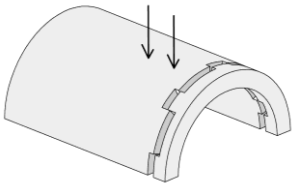
Additional symptom or context condition		**2.1.3**	**2.1.8**
G:	damage appears in spandrel wall	·	■
G:	presence of backfill behind spandrel wall	·	■
T:	damage has appeared after the following occurrence	■	·
E:	occurrence of change in use	■	·

D. Further reading

[Harvey 2004] case 25, [Harvey 2004] case 26, [Harvey 2004] case 27.

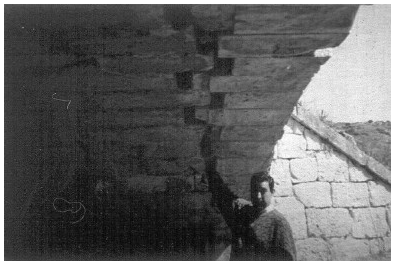
Damage pattern 5
Crack - in arch or barrel vault - parallel to span - in vault web

A. Damage pattern



symptoms:
- ■ S: crack
- ■ S: crack direction is parallel to span

context conditions included in pattern:
- ■ G: damage appears in arch or barrel vault
- ■ G: damage appears in vault web



Examples. [Onsiteformasonry et al. 2002] par. 7.8.4 GEOCISA, [Harvey 2004] case 24, [Onsiteformasonry et al. 2002] par. 7.5.6 ZAG.

B. Hypotheses

☐ 2.1.3 Overloading due to change in load, vertical, increase in use load

C. Essential conditions

Additional symptom or context condition	**2.1.3**
T: damage has appeared after the following occurrence	■
E: occurrence of change in use	■

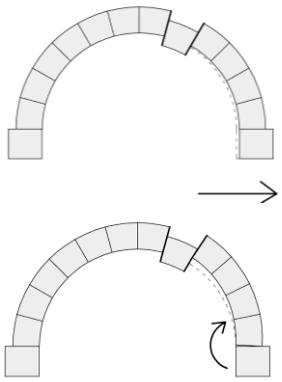
D. Further reading

[Harvey 2004] case 9, [Harvey 2004] case 23, [Harvey 2004] case 24, [Onsiteformasonry et al. 2002] par. 7.5.6 ZAG, [Onsiteformasonry et al. 2002] par. 7.8.4 GEOCISA.

Damage pattern 6

Crack - in arch or barrel vault - perpendicular to span - in-plane displacement, parallel to crack

A. Damage pattern



symptoms:

- ■ S: crack
- ■ S: crack direction is perpendicular to span
- ■ S: in-plane displacement, parallel to crack

context conditions included in pattern:

- ■ G: damage appears in arch or barrel vault

Examples. [Ceci et al. 2010] Fig. 15e, [Croci 1998] Fig. 2.41, [Lourenço 2005] Fig. 3.

B. Hypotheses

- ☐ 2.1.1 Overloading due to change in load, vertical, increase in self-weight, at time of construction
- ☐ 2.1.2 Overloading due to change in load, vertical, increase in self-weight, extensions built in or onto building
- ☐ 2.1.3 Overloading due to change in load, vertical, increase in use load
- ☐ 2.1.11 Overloading due to change in load, horizontal, impact of object hitting edge
- ☐ 2.1.15 Overloading due to change in load, vibrational, natural or induced earthquake
- ☐ 2.1.16 Overloading due to change in load, vibrational, machinery or traffic
- ☐ 2.3.9 Overloading due to change in resistance, decrease in capacity of masonry, due to creep

C. Essential conditions

Additional symptom or context condition		2.1.1	2.1.2	2.1.3	2.1.11	2.1.15
G:	damage appears in external building component	·	·	·	■	·
G:	damage appears at protruding edge	·	·	·	■	·
T:	damage has appeared after the following occurrence	·	■	■	·	■
G:	occurrence of extension built in or on top of existing building	·	■	·	·	·
E:	occurrence of change in use	·	·	■	·	·
E:	occurrence of seismic event	·	·	·	·	■
T:	damage has appeared in the first years after construction	■	·	·	·	·

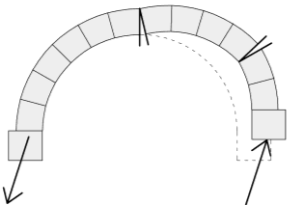
Additional symptom or context condition		2.1.16	2.3.9
M:	presence of lime-based mortar	·	■
G:	presence of high (gravity) load	·	■
T:	damage has appeared after the following occurrence	■	·
E:	occurrence of vibrations with considerable amplitude, due to machinery or traffic	■	·
T:	damage has appeared gradually, over a considerable period of time	·	■

D. Further reading

[Ceci et al. 2010] Fig. 15e, [Croci 1998] Fig. 2.29 k, [Croci 1998] Fig. 2.29 l, [Croci 1998] Fig. 2.41, [Feilden 2003] Fig. 8.2, [Harvey 2004] case 5, [Harvey 2004] case 13, [Harvey 2004] case 14, [Lourenço 2005] Fig. 3, [Schubert 2009] case 2.3.3.4, [Warren 1999] Fig. 11.3.

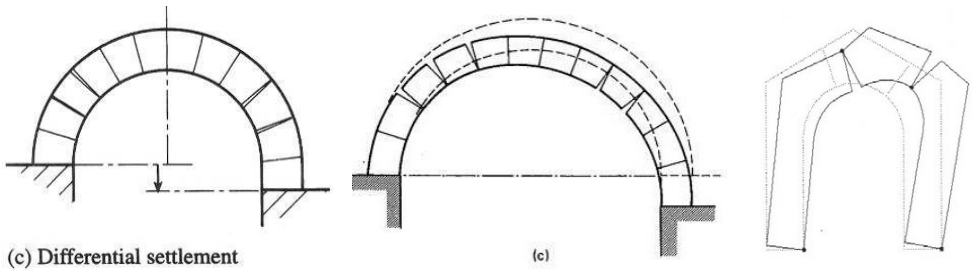
Damage pattern 7
Crack - in arch or barrel vault - perpendicular to span - in-plane displacement, perpendicular to crack - one intrados crack - one extrados crack

A. Damage pattern



symptoms:
- ■ S: crack
- ■ S: crack direction is perpendicular to span
- ■ S: in-plane displacement, perpendicular to crack

context conditions included in pattern:
- ■ G: damage appears in arch or barrel vault
- ■ G: one crack appears at intrados
- ■ G: one crack appears at extrados



Examples. [Beckmann and Bowles 2004] fig. 4.14c, [Feilden 2003] Fig. 3.2c, [Protezione Civile 2006].

B. Hypotheses

- ☐ 1.B Vertical settlement: one-end-settlement / one-end-heave
- ☐ 2.1.15 Overloading due to change in load, vibrational, natural or induced earthquake
- ☐ 2.1.16 Overloading due to change in load, vibrational, machinery or traffic

NB Two types of failure can occur with increasing span:
1. Strong-buttress, in which the arch collapses leaving the buttress intact
2. Weak-buttress, in which the buttress capacity for horizontal thrust is exceeded, causing the buttress to rotate additionally, and the arch collapses. [Ochsendorf 2006]

C. Essential conditions

For hypotheses and corresponding essential conditions of vertical settlement, see Part III of this tool.

	Additional symptom or context condition	1.B	2.1.15	2.1.16
T:	damage has appeared after the following occurrence	·	■	■
E:	occurrence of seismic event	·	■	·
E:	occurrence of vibrations with considerable amplitude, due to machinery or traffic	·	·	■
E:	occurrence of removal of mid-terrace building	·	·	·
T:	damage has appeared gradually, over a considerable period of time	·	·	·
T:	damage has appeared in the first years after construction	·	·	·

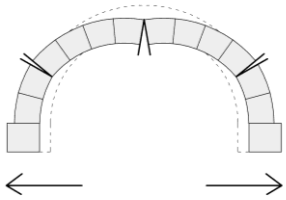
D. Further reading

[Beckmann and Bowles 2004] fig. 4.14c, [Feilden 2003] Fig. 3.2c, [Harvey 2004] case 11, [Harvey 2004] case 18, [Harvey 2004] case 19, [Huerta 2005] Fig. 5b, [Ochsendorf 2004], [Protezione Civile 2006].

Damage pattern 8

Crack - in arch or barrel vault - perpendicular to span - in-plane displacement, perpendicular to crack - one intrados crack - two extrados cracks - symmetrical

A. Damage pattern

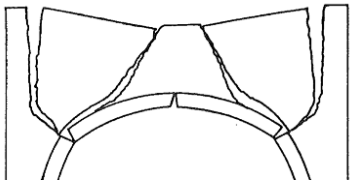


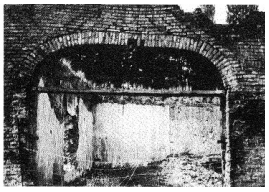
symptoms:

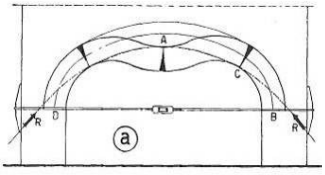
- ■ S: crack
- ■ S: crack direction is perpendicular to span
- ■ S: in-plane displacement, perpendicular to crack
- ■ S: damage is symmetric with respect to a vertical plane along the crown
- ■ S: curve of arch is flattened halfway span (arch sag)

context conditions included in pattern:

- ■ G: damage appears in arch or barrel vault
- ■ G: one crack appears at intrados
- ■ G: two cracks appear at extrados







Examples. [Barthel 1993] Bild 3.1/19a, [Barthel 1993] Bild 3.1/18, [Mastrodicasa 1993] Fig. 146 a.

B. Hypotheses

- ☐ 1.D Horizontal soil movement
- ☐ 2.1.1 Overloading due to change in load, vertical, increase in self-weight, at time of construction
- ☐ 2.1.2 Overloading due to change in load, vertical, increase in self-weight, extensions built in or onto building
- ☐ 2.3.9 Overloading due to change in resistance, decrease in capacity of masonry, due to creep

C. Essential conditions

For hypotheses and corresponding essential conditions of horizontal settlement, see Part III of this tool.

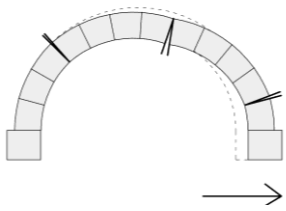
	Additional symptom or context condition	1.D	2.1.1	2.1.2	2.3.9
M:	presence of lime-based mortar	·	·	·	■
G:	presence of high (gravity) load	·	·	·	■
T:	damage has appeared after the following occurrence	·	·	■	·
G:	occurrence of extension built in or on top of existing building	·	·	■	·
T:	damage has appeared gradually, over a considerable period of time	·	·	·	■
T:	damage has appeared in the first years after construction	·	■	·	·

D. Further reading

[Barthel 1993] Bild 3.1/19a, [Barthel 1993] Bild 3.1/18, [Beckmann and Bowles 2004] fig. 4.14b, [Beckmann and Bowles 2004] fig. 4.14d, [Feilden 2003] Fig. 3.2b, [Harvey 2004] case 7, [Mastrodicasa 1993] Fig. 146 a, [Naldini et al. 2007].

Damage pattern 9
Crack - in arch or barrel vault - perpendicular to span - in-plane displacement, perpendicular to crack - one intrados crack - two extrados cracks - asymmetrical

A. Damage pattern



symptoms:

- ■ S: crack
- ■ S: crack direction is perpendicular to span
- ■ S: in-plane displacement, perpendicular to crack
- ■ S: damage is asymmetric with respect to a vertical plane along the crown

context conditions included in pattern:

- ■ G: damage appears in arch or barrel vault
- ■ G: one crack appears at intrados
- ■ G: two cracks appear at extrados

B. Hypotheses

- ☐ 1.D Horizontal soil movement
- ☐ 2.1.1 Overloading due to change in load, vertical, increase in self-weight, at time of construction
- ☐ 2.1.2 Overloading due to change in load, vertical, increase in self-weight, extensions built in or onto building

C. Essential conditions

For hypotheses and corresponding essential conditions of horizontal settlement, see Part III of this tool.

Additional symptom or context condition		1.D	2.1.1	2.1.2
T:	damage has appeared after the following occurrence	·	·	■
G:	occurrence of extension built in or on top of existing building	·	·	■
T:	damage has appeared in the first years after construction	·	■	·

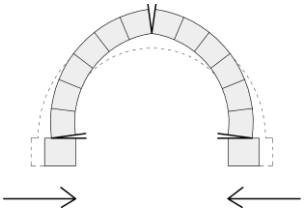
D. Further reading

[Harvey 2004] case 16.

Damage pattern 10

Crack - in arch or barrel vault - perpendicular to span - in-plane displacement, perpendicular to crack - two intrados cracks - one extrados crack - symmetrical

A. Damage pattern

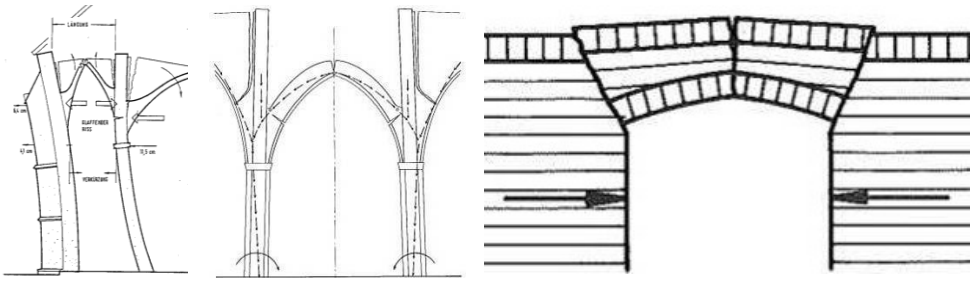


symptoms:

- ■ S: crack
- ■ S: crack direction is perpendicular to span
- ■ S: in-plane displacement, perpendicular to crack
- ■ S: damage is symmetric with respect to a vertical plane along the crown
- ■ S: curve of arch is sharpened to both sides (arch hog)

context conditions included in pattern:

- ■ G: damage appears in arch or barrel vault
- ■ G: two cracks appear at intrados, at or near the springings
- ■ G: one crack appears at extrados, at mid span, at or near crown



Examples. [Barthel 1993] Anlage 3.1/5 (detail), [Pieper 1983] Bild 8.18, [Stichting Bouwresearch 1966] Fig. 76 b.

B. Hypotheses

- ☐ 2.2.9 Overloading due to change in load path, horizontal displacement of supports
- ☐ 3.1.11 Hindered dimensional changes, temperature/moisture induced, lack of flexibility to accommodate movement

C. Essential conditions

Additional symptom or context condition	2.2.9	3.1.11
G: damage appears in support of arch, vault or dome	■	·
S: deviation from vertical: vertical edge is not vertical anymore, out of plumb	■	·
G: damage appears near an opening	·	■
G: absence of sufficient expansion joints	·	■

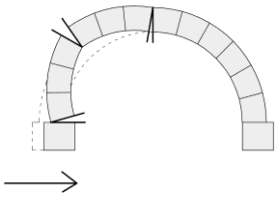
D. Further reading

[Barthel 1993] Anlage 3.1/5 (detail), [Pieper 1983] Bild 8.18, [Stichting Bouwresearch 1966] Fig. 76 b.

Damage pattern 11

Crack - in arch or barrel vault - perpendicular to span - in-plane displacement, perpendicular to crack - two intrados cracks - one extrados crack - asymmetrical

A. Damage pattern



symptoms:

- ■ S: crack
- ■ S: crack direction is perpendicular to span
- ■ S: in-plane displacement, perpendicular to crack
- ■ S: damage is asymmetric with respect to a vertical plane along the crown
- ■ S: curve of arch is sharpened to one side, flattened to other side (arch sway)

context conditions included in pattern:

- ■ G: damage appears in arch or barrel vault
- ■ G: two cracks appear at intrados
- ■ G: one crack appears at extrados

B. Hypotheses

☐ 2.2.9 Overloading due to change in load path, horizontal displacement of supports

C. Essential conditions

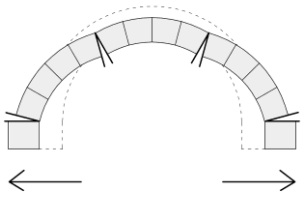
Additional symptom or context condition	**2.2.9**
G: damage appears in support of arch, vault or dome	■
S: deviation from vertical: vertical edge is not vertical anymore, out of plumb	■

D. Further reading

[Harvey 2004] case 16.

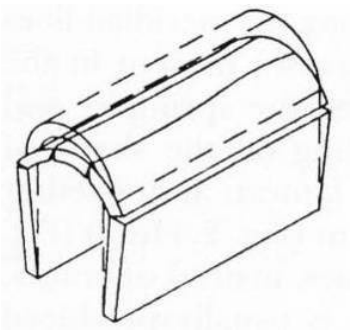
Damage pattern 12
Crack - in arch or barrel vault - perpendicular to span - in-plane displacement, perpendicular to crack - two intrados cracks - two extrados cracks - intrados cracks near crown

A. Damage pattern



symptoms:
- ■ S: crack
- ■ S: crack direction is perpendicular to span
- ■ S: in-plane displacement, perpendicular to crack

context conditions included in pattern:
- ■ G: damage appears in arch or barrel vault
- ■ G: two cracks appear at intrados, at mid span, at or near crown
- ■ G: two cracks appear at extrados, at or near the springings



Example. [Croci 1998] Fig. 2.44 a.

B. Hypotheses

- ☐ 1.D Horizontal soil movement
- ☐ 2.1.1 Overloading due to change in load, vertical, increase in self-weight, at time of construction
- ☐ 2.1.2 Overloading due to change in load, vertical, increase in self-weight, extensions built in or onto building
- ☐ 2.3.9 Overloading due to change in resistance, decrease in capacity of masonry, due to creep

C. Essential conditions

For hypotheses and corresponding essential conditions of horizontal settlement, see Part III of this tool.

	Additional symptom or context condition	1.D	2.1.1	2.1.2	2.3.9
M:	presence of lime-based mortar	·	·	·	■
G:	presence of high (gravity) load	·	·	·	■
T:	damage has appeared after the following occurrence	·	·	■	·
G:	occurrence of extension built in or on top of existing building	·	·	■	·
T:	damage has appeared gradually, over a considerable period of time	·	·	·	■
T:	damage has appeared in the first years after construction	·	■	·	·

NB Note that this damage pattern points, in principle, to an unstable situation.

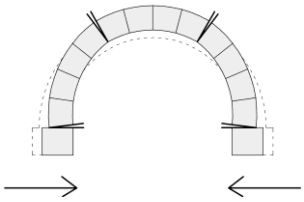
D. Further reading

[Croci 1998] Fig. 2.44 a.

Damage pattern 13

Crack - in arch or barrel vault - perpendicular to span - in-plane displacement, perpendicular to crack - two intrados cracks - two extrados cracks - intrados cracks near springings

A. Damage pattern



symptoms:

- ■ S: crack
- ■ S: crack direction is perpendicular to span
- ■ S: in-plane displacement, perpendicular to crack

context conditions included in pattern:

- ■ G: damage appears in arch or barrel vault
- ■ G: two cracks appear at intrados, at or near the springings
- ■ G: two cracks appear at extrados, at mid span, at or near crown

B. Hypotheses

☐ 2.2.9 Overloading due to change in load path, horizontal displacement of supports

C. Essential conditions

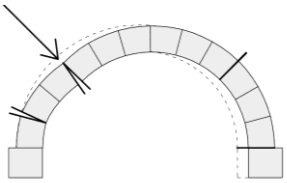
Additional symptom or context condition	**2.2.9**
G: damage appears in support of arch, vault or dome	■
S: deviation from vertical: vertical edge is not vertical anymore, out of plumb	■

NB Note that this damage pattern points, in principle, to an unstable situation.

Damage pattern 14

Crack - in arch or barrel vault - perpendicular to span - in-plane displacement, perpendicular to crack - two intrados cracks - two extrados cracks - one intrados crack near top, one intrados crack near springings

A. Damage pattern



symptoms:

- ■ S: crack
- ■ S: crack direction is perpendicular to span
- ■ S: in-plane displacement, perpendicular to crack

context conditions included in pattern:

- ■ G: damage appears in arch or barrel vault
- ■ G: two cracks appear at intrados: one crack at mid span, at or near crown, one crack at or near the springings
- ■ G: two cracks appear at extrados: one crack at mid span, at or near crown, one crack at or near the springings

B. Hypotheses

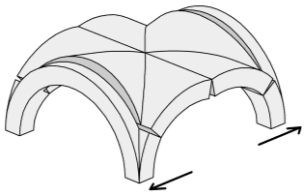
☐ 2.1.3 Overloading due to change in load, vertical, increase in use load

C. Essential conditions

Additional symptom or context condition	**2.1.3**
T: damage has appeared after the following occurrence	■
E: occurrence of change in use	■

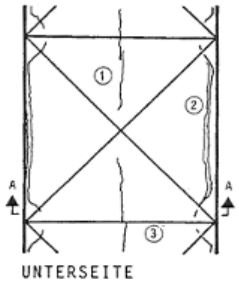
Damage pattern 15
Crack - in cross-vault or dome - intrados crack(s) near crown

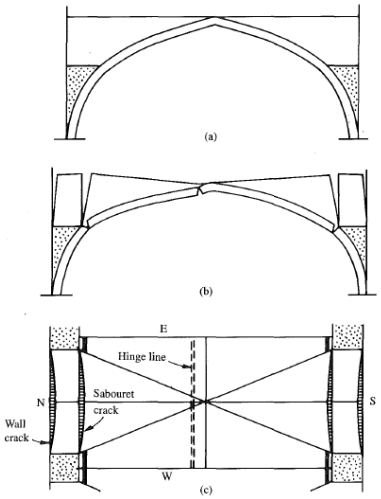
A. Damage pattern



symptoms:
- ■ S: crack

context conditions included in pattern:
- ■ G: damage appears in cross-vault or dome
- ■ G: one crack appears at intrados, at mid span, at or near crown
- ■ G: two cracks appear at extrados, at or near the springings





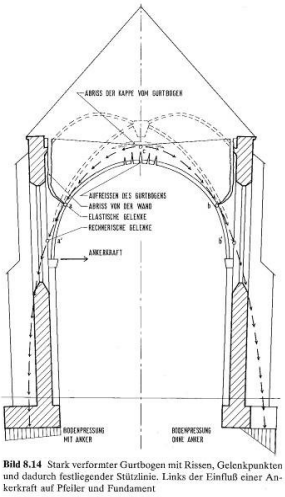


Bild 8.14 Stark verformter Gurtbogen mit Rissen, Gelenkpunkten und dadurch festliegender Stützlinie. Links der Einfluß einer Ankerkraft auf Pfeiler und Fundament

Examples. [Barthel 1993] Bild 3.1/1 (detail), [Heyman 1995] Fig. 4.24, [Pieper 1983] Bild 8.14.

B. Hypotheses

- ☐ 1.D Horizontal soil movement
- ☐ 2.1.1 Overloading due to change in load, vertical, increase in self-weight, at time of construction
- ☐ 2.1.2 Overloading due to change in load, vertical, increase in self-weight, extensions built in or onto building
- ☐ 2.3.9 Overloading due to change in resistance, decrease in capacity of masonry, due to creep

C. Essential conditions

For hypotheses and corresponding essential conditions of horizontal settlement, see Part III of this tool.

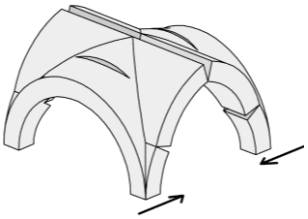
	Additional symptom or context condition	1.D	2.1.1	2.1.2	2.3.9
M:	presence of lime-based mortar	·	·	·	■
G:	presence of high (gravity) load	·	·	·	■
T:	damage has appeared after the following occurrence	·	·	■	·
G:	occurrence of extension built in or on top of existing building	·	·	■	·
T:	damage has appeared gradually, over a considerable period of time	·	·	·	■
T:	damage has appeared in the first years after construction	·	■	·	·

D. Further reading

[Barthel 1993] Bild 3.1/1, [Barthel 1993] Bild 3.1/19b, [Barthel 1993] Anlage 3.1/5 (detail), [Ceci et al. 2010] Fig. 15g, [Croci 1998] Fig. 2.44 c, [Croci 1998] Fig. 2.44 d, [Harvey 2004] case 2, [Harvey 2004] case 8, [Harvey 2004] case 17, [Heyman 1995] Fig.4.24, [Lourenço 2005] Fig. 5a, [Pieper 1983] Bild 8.14, [Pieper 1983] Bild 18.18, [Pieper 1983] Bild 8.23 2, 4, 5.

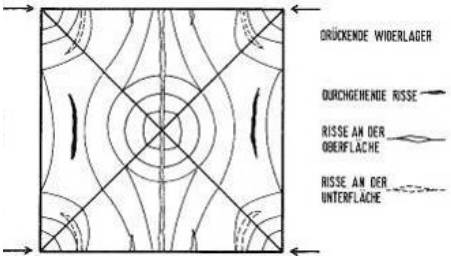
Damage pattern 16
Crack - in cross-vault or dome - intrados cracks near springings - extrados crack(s) near crown

A. Damage pattern



symptoms:
- ■ S: crack

context conditions included in pattern:
- ■ G: damage appears in cross-vault or dome
- ■ G: one crack appears at extrados, at mid span, at or near crown
- ■ G: two cracks appear at intrados, at or near the springings



Examples. [Pieper 1983] Bild 8.23 3

B. Hypotheses

☐ 2.2.9 Overloading due to change in load path, horizontal displacement of supports

C. Essential conditions

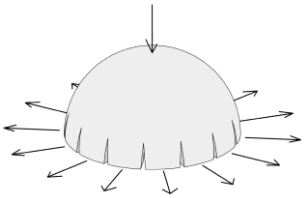
Additional symptom or context condition	**2.2.9**
G: damage appears in support of arch, vault or dome	■
S: deviation from vertical: vertical edge is not vertical anymore, out of plumb	■

D. Further reading

[Pieper 1983] Bild 8.23 3

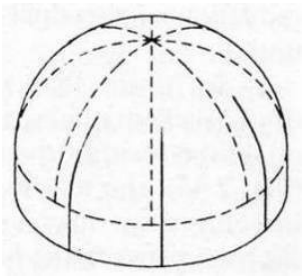
Damage pattern 17
Crack - in cross-vault or dome - intrados cracks near springings - extrados cracks near springings

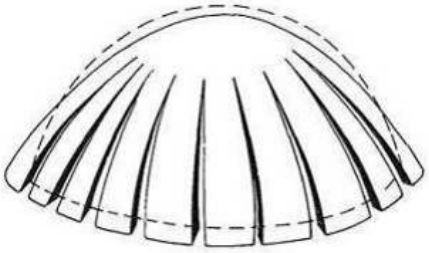
A. Damage pattern



symptoms:
- ■ S: crack
- ■ S: multiple cracks
- ■ S: crack direction is vertical
- ■ S: crack is tapered towards one end
- ■ S: crack is widest at bottom, narrowest at top

context conditions included in pattern:
- ■ G: damage appears in cross-vault or dome
- ■ G: damage appears at or near the springings





Examples. [Croci 1998] Fig. 2.44 f, [Heyman 1995] Fig. 3.7, [Meichsner and Rohr-Suchalla 2008] Bild 167.

B. Hypotheses

- ☐ 1.D Horizontal soil movement
- ☐ 2.1.1 Overloading due to change in load, vertical, increase in self-weight, at time of construction
- ☐ 2.1.2 Overloading due to change in load, vertical, increase in self-weight, extensions built in or onto building

C. Essential conditions

For hypotheses and corresponding essential conditions of horizontal settlement, see Part III of this tool.

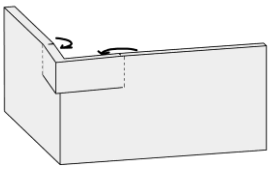
Additional symptom or context condition		1.D	2.1.1	2.1.2
T:	damage has appeared after the following occurrence	·	·	■
G:	occurrence of extension built in or on top of existing building	·	·	■
T:	damage has appeared in the first years after construction	·	■	·

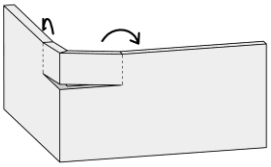
D. Further reading

[Croci 1998] Fig. 2.44 e, [Croci 1998] Fig. 2.44 f, [Heyman 1995] Fig. 3.7, [Meichsner and Rohr-Suchalla 2008] Bild 167, [Pieper 1983] Bild 8.40.

Damage pattern 18
Crack - in column or wall - horizontal - at a corner

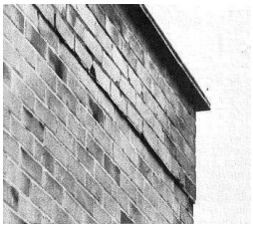
A. Damage pattern

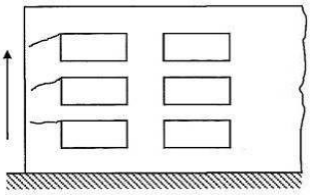


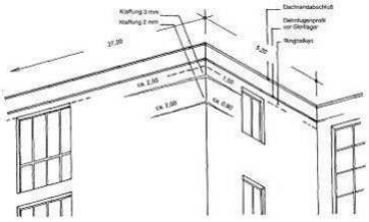


symptoms:
- ■ S: crack
- ■ S: crack direction is horizontal

context conditions included in pattern:
- ■ G: damage appears in column or wall
- ■ G: damage appears at a corner







Examples. [Addleson 1989] p.51, [Hendry and Khalaf 2001] Fig 7.1 d, [Pfefferkorn 1994] Bild 39.

B. Hypotheses

- ☐ 3.1.3 Hindered dimensional changes, temperature/moisture induced, difference in behaviour between masonry and concrete
- ☐ 3.1.5 Hindered dimensional changes, temperature/moisture induced, difference in conditions between shady and sunny side
- ☐ 3.1.8 Hindered dimensional changes, temperature/moisture induced, abrupt extreme change in moisture content, irreversible shrinkage of unfired artificial stone after production
- ☐ 3.2 Hindered dimensional changes, due to frost action

C. Essential conditions

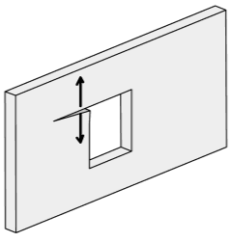
Additional symptom or context condition		3.1.3	3.1.5	3.1.8	3.2
M:	presence of a concrete floor slab	①	·	·	·
M:	presence of a concrete roof slab	③	·	·	·
M:	presence of a concrete beam	④	·	·	·
M:	damage appears in unfired artificial stone units	·	·	■	·
G:	damage appears in external building component	·	·	·	■
G:	damage appears with maximum at or near floor level	①	·	·	·
G:	damage appears at or just below roof level	③	·	·	·
G:	damage appears with maximum at or just below level of beam	④	·	·	·
E:	presence of source of moisture	·	·	·	■
G:	absence of sufficient expansion joints	·	■	·	·
G:	damage appears at corner	·	■	·	·
G:	damage appears at roof edge, in parapet wall	·	·	·	■
E:	occurrence of temperatures below freezing point	·	·	·	■
T:	damage has appeared in the first years after construction	·	·	■	·

D. Further reading

[Addleson 1989] p.51, [Bakker 1963] Fig. 166, [Eldridge 1976] p. 114, [Eldridge 1976] p. 152, [Eldridge 1976] p.160, [Hendry and Khalaf 2001] Fig 7.1 d, [Hinks and Cook 1997] Fig. 10.14a, [Meichsner and Rohr-Suchalla 2008] p. 37, [Meichsner and Rohr-Suchalla 2008] Bild 183, [Meichsner and Rohr-Suchalla 2008] Bild 186, [Meichsner and Rohr-Suchalla 2008] Bild 189, [Meichsner and Rohr-Suchalla 2008] Bild 195, [Meichsner and Rohr-Suchalla 2008] Bild 196, [Pfefferkorn 1994] Bild 37, [Pfefferkorn 1994] Bild 39, [Pfefferkorn 1994] Bild 48, [Schubert 2009] case 2.1.1.2, [Schubert 2009] case 2.1.1.2, [Schubert 2009] case 2.1.1.5, [Schubert 2009] case 2.1.1.6.

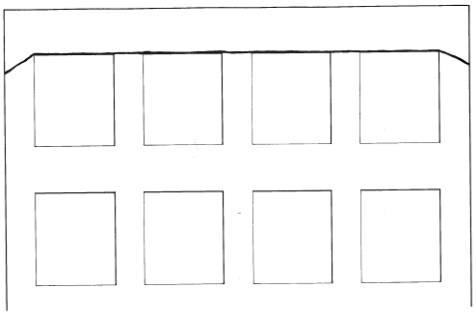
Damage pattern 19
Crack - in column or wall - horizontal - near an opening

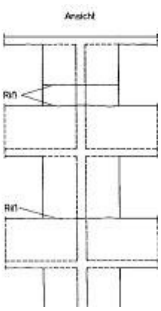
A. Damage pattern

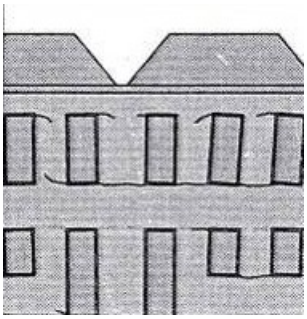


symptoms:
- ■ S: crack
- ■ S: crack direction is horizontal

context conditions included in pattern:
- ■ G: damage appears in column or wall
- ■ G: damage appears near an opening







Examples. [Eldridge 1976] p. 130, [Pfefferkorn 1994] Bild 9a, [van Stigt 1995].

B. Hypotheses

- ☐ 1.A Vertical settlement: mid-settlement / both-ends-heave
- ☐ 1.B Vertical settlement: one-end-settlement / one-end-heave
- ☐ 1.C Vertical settlement: both-ends-settlement / mid-heave
- ☐ 2.1.1 Overloading due to change in load, vertical, increase in self-weight, at time of construction
- ☐ 2.1.2 Overloading due to change in load, vertical, increase in self-weight, extensions built in or onto building
- ☐ 2.1.4 Overloading due to change in load, horizontal, push of wind
- ☐ 2.1.6 Overloading due to change in load, horizontal, thrust of flat arch lintel
- ☐ 2.2.6 Overloading due to change in load path, bending, of floor that supports damaged wall
- ☐ 2.2.8 Overloading due to change in load path, bending, of lintel
- ☐ 2.3.5 Overloading due to change in resistance, geometrical discontinuities in a cavity wall (wall tie deficiencies)

☐ 3.1.3 Hindered dimensional changes, temperature/moisture induced, difference in behaviour between masonry and concrete
☐ 3.1.7 Hindered dimensional changes, temperature/moisture induced, difference in conditions between in-doors and out-of-doors
☐ 3.1.8 Hindered dimensional changes, temperature/moisture induced, abrupt extreme change in moisture content, irreversible shrinkage of unfired artificial stone after production
☐ 3.1.11 Hindered dimensional changes, temperature/moisture induced, lack of flexibility to accommodate movement

C. Essential conditions

For hypotheses and corresponding essential conditions of vertical settlement, see Part III of this tool.

Additional symptom or context condition	1.A	1.B	1.C	2.1.1	2.1.2
T: damage has appeared after the following occurrence	·	·	·	·	■
G: occurrence of extension built in or on top of existing building	·	·	·	·	■
T: damage has appeared in the first years after construction	·	·	·	■	·

Additional symptom or context condition	2.1.4	2.1.6	2.2.6	2.2.8	2.3.5
G: damage appears in external building component	■	·	·	·	·
G: damage appears at or just below support of lintel	·	■	·	·	·
G: presence of flat arch lintel	·	■	·	·	·
G: damage appears in wall that is supported by floor	·	·	■	·	·
G: damage appears next to and above lintel	·	·	·	■	·
G: damage appears in cavity wall	·	·	·	·	■

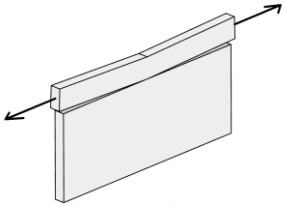
Additional symptom or context condition	3.1.3	3.1.7	3.1.8	3.1.11
M: presence of a concrete roof slab	③	·	·	·
M: presence of a concrete beam	④	·	·	·
M: damage appears in unfired artificial stone units	·	·	■	·
G: damage appears at or just below roof level	③	·	·	·
G: damage appears near an opening	·	·	·	■
G: damage appears with maximum at or just below level of beam	④	·	·	·
G: damage appears in cavity wall	·	·	·	·
G: absence of sufficient expansion joints	·	■	·	■
G: damage appears at connection between internal and external wall	·	■	·	·
T: damage has appeared in the first years after construction	·	·	■	·

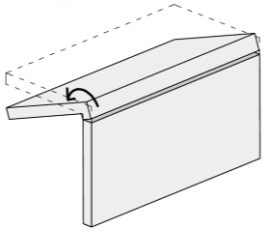
D. Further reading

[Cook and Hinks 1992] Fig. 3.1a, [Cook and Hinks 1992] Fig. 3.1b, [Cook and Hinks 1992] Fig. 3.2a, [Eldridge 1976] p. 130, [Meichsner and Rohr-Suchalla 2008] Bild 221, [Meichsner and Rohr-Suchalla 2008] Bild 224, [Pfefferkorn 1994] Bild 9a, [Schubert 2009] case 2.1.1.1, [Schubert 2009] case 2.3.3.1, [Stichting Bouwresearch 1966] Fig. 78, [Stichting Bouwresearch 1976] p. 47, [van Stigt 1995].

Damage pattern 20
Crack - in column or wall - horizontal - halfway the length - near roof or floor level

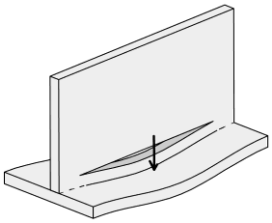
A. Damage pattern

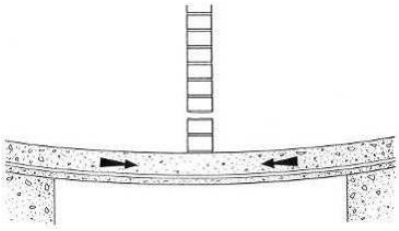


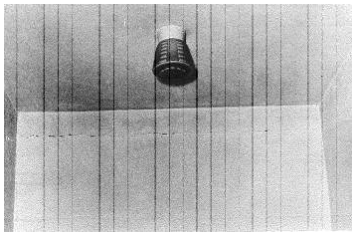


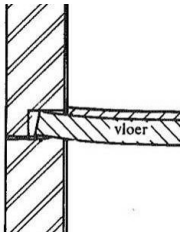
symptoms:
- ■ S: crack
- ■ S: crack direction is horizontal

context conditions included in pattern:
- ■ G: damage appears in column or wall
- ■ G: damage appears with maximum halfway the length









Examples. [Eldridge 1976] p. 265, [Stichting Bouwresearch 1966] Fig. 29, [Stichting Bouwresearch 1966] Fig. 32.

B. Hypotheses

- ☐ 2.1.5 Overloading due to change in load, horizontal, thrust of arch, vault or dome
- ☐ 2.1.7 Overloading due to change in load, horizontal, thrust of roof truss
- ☐ 2.1.15 Overloading due to change in load, vibrational, natural or induced earthquake
- ☐ 2.1.16 Overloading due to change in load, vibrational, machinery or traffic
- ☐ 2.2.5 Overloading due to change in load path, bending, of floor supported by damaged wall
- ☐ 2.2.6 Overloading due to change in load path, bending, of floor that supports damaged wall
- ☐ 3.1.3 Hindered dimensional changes, temperature/moisture induced, difference in behaviour between masonry and concrete

☐ 3.1.4 Hindered dimensional changes, temperature/moisture induced, difference in behaviour between masonry and timber

☐ 3.1.7 Hindered dimensional changes, temperature/moisture induced, difference in conditions between in-doors and out-of-doors

☐ 3.1.8 Hindered dimensional changes, temperature/moisture induced, abrupt extreme change in moisture content, irreversible shrinkage of unfired artificial stone after production

C. Essential conditions

Additional symptom or context condition		2.1.5	2.1.7	2.1.15	2.1.16	2.2.5
G:	damage appears at or just below the springings	■ ■	·	·	·	·
G:	presence of arch, vault or dome adjacent to damaged area	■	·	·	·	·
G:	damage appears at or just below roof level	·	■	·	·	·
G:	damage appears in wall that supports the floor	·	·	·	·	■
G:	damage appears with maximum at or near floor level	·	·	·	·	■
T:	damage has appeared after the following occurrence	·	·	■	■	·
E:	occurrence of seismic event	·	·	■	·	·
E:	occurrence of vibrations with considerable amplitude, due to machinery or traffic	·	·	·	■	·

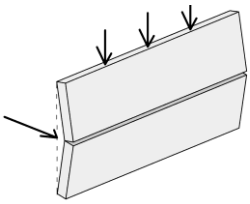
Additional symptom or context condition		2.2.6	3.1.3	3.1.4	3.1.7	3.1.8
M:	presence of a concrete frame, with masonry used as infill	·	⑤	·	·	·
M:	presence of a concrete floor slab	·	①	·	·	·
M:	presence of a concrete roof slab	·	③	·	·	·
M:	presence of timber beam	·	·	■	·	·
M:	damage appears in unfired artificial stone units	·	·	·	·	■
G:	damage appears at or just below roof level	·	③	·	·	·
G:	damage appears with maximum at or near floor level	·	①	·	·	·
G:	damage appears in wall that is supported by floor	■	·	·	·	·
G:	damage appears with maximum at or just below level of beam	·		■	·	·
G:	absence of sufficient expansion joints	·	·	·	■	·
G:	damage appears at connection between internal and external wall	·	·	·	■	·
T:	damage has appeared in the first years after construction	·	·	·	·	■

D. Further reading

[Addleson 1989] Fig. 9, [Addleson 1989] p.92 Fig 1b, [Addleson 1989] p. 103 Fig. 6, [Douglas and Ransom 2007] Fig. 11.3, [Eldridge 1976] p.133, [Eldridge 1976] p. 127, [Eldridge 1976] p.166, [Eldridge 1976] p 218, [Eldridge 1976] p. 265, [Meichsner and Rohr-Suchalla 2008] Bild 184, [Marshall et al. 2009] p. 192 d, [Meichsner and Rohr-Suchalla 2008] Bild 198, [Meichsner and Rohr-Suchalla 2008] Bild 201, [Pfefferkorn 1994] Bild 198, [Protezione Civile 2006], [Richardson 2001] plate 46, [Schubert 2009] case 2.1.1.3, [Schubert 2009] case 2.2.1.1, [Schubert 2009] case 2.5.1, [Stichting Bouwresearch 1966] Fig. 29, [Stichting Bouwresearch 1966] Fig. 32, [Stichting Bouwresearch 1966] Fig.39a, [Stichting Bouwresearch 1966] Fig.39b, [van Stigt 1995].

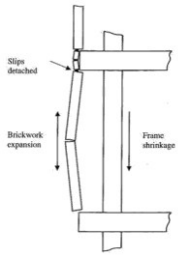
Damage pattern 21
Crack - in column or wall - horizontal - halfway the length - not near roof or floor level

A. Damage pattern



symptoms:
- ■ S: crack
- ■ S: crack direction is horizontal

context conditions included in pattern:
- ■ G: damage appears in column or wall
- ■ G: damage appears with maximum halfway the length
- ■ G: damage appears with maximum halfway between two floors



Examples. [Hendry and Khalaf 2001] Fig 7.5, [Eldridge 1976] p. 124, [Marshall et al. 2009] p. 84.

B. Hypotheses

- ☐ 1.A Vertical settlement: mid-settlement / both-ends-heave
- ☐ 1.B Vertical settlement: one-end-settlement / one-end-heave
- ☐ 1.C Vertical settlement: both-ends-settlement / mid-heave
- ☐ 3.1.1 Hindered dimensional changes, temperature/moisture induced, difference in behaviour between two types of units in masonry
- ☐ 3.1.3 Hindered dimensional changes, temperature/moisture induced, difference in behaviour between masonry and concrete
- ☐ 3.1.5 Hindered dimensional changes, temperature/moisture induced, difference in conditions between shady and sunny side
- ☐ 3.1.7 Hindered dimensional changes, temperature/moisture induced, difference in conditions between in-doors and out-of-doors
- ☐ 3.1.8 Hindered dimensional changes, temperature/moisture induced, abrupt extreme change in moisture content, irreversible shrinkage of unfired artificial stone after production

☐ 3.1.9 Hindered dimensional changes, temperature/moisture induced, abrupt extreme change in moisture content, irreversible swelling of fired clay bricks after production
☐ 3.2 Hindered dimensional changes, due to frost action
☐ 3.3 Hindered dimensional changes, due to corrosion
☐ 3.4.2 Hindered dimensional changes, due to salt attack, formation of swelling compounds

C. Essential conditions

For hypotheses and corresponding essential conditions of vertical settlement, see Part III of this tool.

Additional symptom or context condition	1.A	1.B	1.C	3.1.1	3.1.3
M: presence of a concrete frame, with masonry used as infill	·	·	·	·	■
M: damage appears at or near connection between two types of units	·	·	·	■	·
M: presence of two types of units	·	·	·	■	·

Additional symptom or context condition	3.1.5	3.1.7	3.1.8	3.1.9	3.2
M: damage appears in unfired artificial stone units	·	·	■	·	·
M: damage appears in fired clay brick units	·	·	·	■	·
M: presence of clay bricks that were freshly produced at time of construction	·	·	·	■	·
G: damage appears in external building component	·	·	·	·	■
E: presence of source of moisture	·	·	·	·	■
G: absence of sufficient expansion joints	■	■	·	·	·
G: damage appears at corner	■	·	·	·	·
G: damage appears at connection between internal and external wall	·	■	·	·	·
G: damage appears at roof edge, in parapet wall	·	·	·	·	■
E: occurrence of temperatures below freezing point	·	·	·	·	■
T: damage has appeared in the first years after construction	·	·	■	■	·

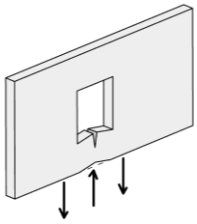
Additional symptom or context condition	3.3	3.4.2
S: rust stains	■	·
S: deformation	·	■
S: deformation out-of-plane	·	■
S: deformation out-of-plane, outward	·	■
M: damage appears at location of iron element	■	·
M: presence of iron element embedded in masonry	■	·
M: damage appears in joints	·	■
S: crack	·	■
S: crack direction is horizontal	·	■
G: damage appears in external building component	·	■
E: presence of source of moisture	·	■
E: presence of source of salt	·	■

D. Further reading

[Addleson 1989] p.77 Fig 18, [Bakker 1963] Fig. 49, [Eldridge 1976] p. 120, [Hendry and Khalaf 2001] Fig 7.5, [Eldridge 1976] p. 124, [Marshall et al. 2009] p. 49 b, [Marshall et al. 2009] p. 81 a, [Marshall et al. 2009] p. 84, [Pfefferkorn 1994] Bild 9b, [Schubert 2009] case 2.3.2, [van Stigt 1995].

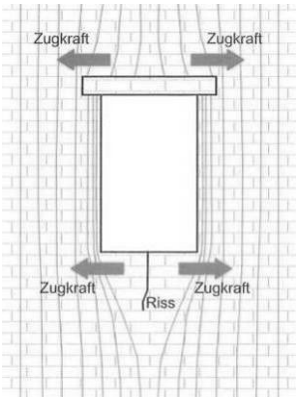
Damage pattern 22
Crack - in column or wall - vertical - tapered towards one end - widest at top - below an opening

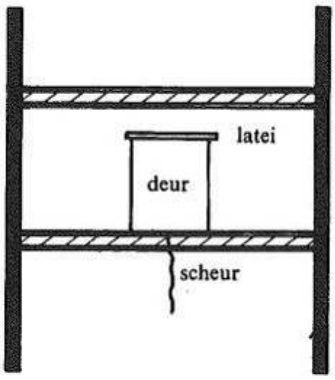
A. Damage pattern



symptoms:
- ■ S: crack
- ■ S: crack direction is vertical
- ■ S: crack is tapered towards one end
- ■ S: crack is widest at top, narrowest at bottom

context conditions included in pattern:
- ■ G: damage appears in column or wall
- ■ G: damage appears below an opening





Examples. [Meichsner and Rohr-Suchalla 2008] Bild 168, [Meichsner and Rohr-Suchalla 2008] Bild 171, [Stichting Bouwresearch 1966] Fig. 4.

B. Hypotheses

- ☐ 1.C Vertical settlement: both-ends-settlement / mid-heave
- ☐ 2.3.1 Overloading due to change in resistance, geometrical discontinuities near opening
- ☐ 3.1.11 Hindered dimensional changes, temperature/moisture induced, lack of flexibility to accommodate movement

C. Essential conditions

For hypotheses and corresponding essential conditions of vertical settlement, see Part III of this tool.

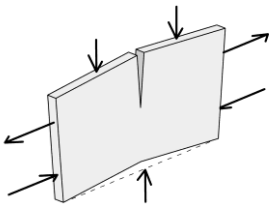
Additional symptom or context condition	1.C	2.3.1	3.1.11
G: damage appears near an opening	·	■	■
G: absence of sufficient expansion joints	·	·	■

D. Further reading

[Addleson 1989] p.76 Fig 16, [Meichsner and Rohr-Suchalla 2008] Bild 168, [Meichsner and Rohr-Suchalla 2008] Bild 169, [Meichsner and Rohr-Suchalla 2008] Bild 171, [Pfefferkorn 1994] Bild 95, [Schubert 2009] case 2.1.2.2, [Stichting Bouwresearch 1966] Fig. 4.

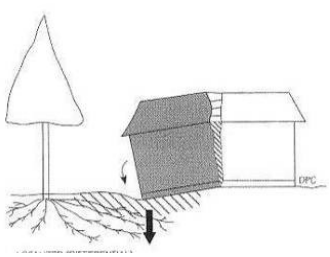
Damage pattern 23
Crack - in column or wall - vertical - tapered towards one end - widest at top - at top of building

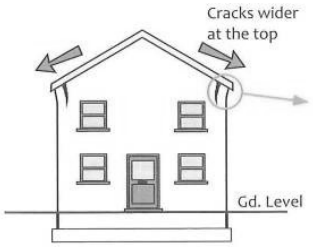
A. Damage pattern

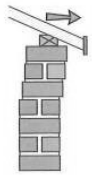


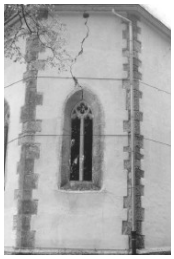
symptoms:
- ■ S: crack
- ■ S: crack direction is vertical
- ■ S: crack is tapered towards one end
- ■ S: crack is widest at top, narrowest at bottom

context conditions included in pattern:
- ■ G: damage appears in column or wall
- ■ G: damage appears with maximum at top









Examples. [Hinks and Cook 1997] Fig. 8.8a, [Marshall et al. 2009] p. 37 j, k, [Onsiteformasonry et al. 2002] par. 7.6.7 ZAG.

B. Hypotheses

☐ 1.B	Vertical settlement: one-end-settlement / one-end-heave
☐ 1.C	Vertical settlement: both-ends-settlement / mid-heave
☐ 2.1.5	Overloading due to change in load, horizontal, thrust of arch, vault or dome
☐ 2.1.7	Overloading due to change in load, horizontal, thrust of roof truss
☐ 2.1.15	Overloading due to change in load, vibrational, natural or induced earthquake
☐ 2.1.16	Overloading due to change in load, vibrational, machinery or traffic
☐ 3.1.3	Hindered dimensional changes, temperature/moisture induced, difference in behaviour between masonry and concrete
☐ 3.1.5	Hindered dimensional changes, temperature/moisture induced, difference in conditions between shady and sunny side
☐ 3.1.7	Hindered dimensional changes, temperature/moisture induced, difference in conditions between in-doors and out-of-doors

C. Essential conditions

For hypotheses and corresponding essential conditions of vertical settlement, see Part III of this tool.

Additional symptom or context condition		1.B	1.C	2.1.5	2.1.7	2.1.15
G:	damage appears at or just below the springings	·	·	■	·	·
G:	presence of arch, vault or dome adjacent to damaged area	·	·	■	·	·
G:	damage appears at or just below roof level	·	·	·	■	·
T:	damage has appeared after the following occurrence	·	·	·	·	■
E:	occurrence of seismic event	·	·	·	·	■

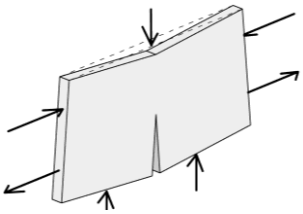
Additional symptom or context condition		2.1.16	3.1.3	3.1.5	3.1.7
M:	presence of a concrete floor slab	·	①	·	·
M:	presence of a concrete roof slab	·	③	·	·
M:	presence of a concrete beam	·	④	·	·
G:	damage appears with maximum at or near floor level	·	①	·	·
G:	damage appears at or just below roof level	·	③	·	·
G:	damage appears with maximum at or just below level of beam	·	④	·	·
G:	absence of sufficient expansion joints	·	·	■	■
G:	damage appears at corner	·	·	■	·
G:	damage appears at connection between internal and external wall	·	·	·	■
T:	damage has appeared after the following occurrence	■	·	·	·
E:	occurrence of vibrations with considerable amplitude, due to machinery or traffic	■	·	·	·

D. Further reading

[Ceci et al. 2010] Fig. 2e, [Croci 1998] Fig. 2.29 b, [Croci 1998] Fig. 5.10 b1, [Croci 1998] Fig. 6.30, [Eldridge 1976] p. 88, [Eldridge 1976] p. 138, [Hendry and Khalaf 2001] Fig 7.3 a, [Hendry and Khalaf 2001] Fig. 7.3 d, [Hinks and Cook 1997] Fig. 8.5a, [Hinks and Cook 1997] Fig. 8.5b, [Hinks and Cook 1997] Fig. 8.8a, [Hinks and Cook 1997] Fig. 8.8b, [Hinks and Cook 1997] Fig. 8.10, [Hinks and Cook 1997] Fig. 10.15, [Hinks and Cook 1997] Fig. 10.17, [Kastner et al. 2003] Fig. 2.2, [Kastner et al. 2003] Fig. 4.1, [Kastner et al. 2003] Fig. 4.3, [Kastner et al. 2003] Fig. 4.4, [Marshall et al. 2009] p. 22 c, [Marshall et al. 2009] p. 23, [Marshall et al. 2009] p.27, [Marshall et al. 2009] p. 37 j, k, [Marshall et al. 2009] p. 37 l, [Mastrodicasa 1993] Fig 57 a, [Mastrodicasa 1993] Fig. 70a, [Mastrodicasa 1993]Fig. 71a, [Mastrodicasa 1993] Fig. 95, [Mastrodicasa 1993] Fig 96, [Meichsner and Rohr-Suchalla 2008] Bild 179, [Naldini et al. 2007], [Onsiteformasonry et al. 2002] par. 7.6.7 ZAG, [Pfefferkorn 1994] Bild 88, [Pfefferkorn 1994] Bild 22, [Pieper 1983] Bild 13.22, [Stichting Bouwresearch 1966] Fig. 20, [Stichting Bouwresearch 1975] Foto 20, [van Stigt 1995], [TNO DIANA BV 2008] example Wall, [Warren 1999] Fig. 5.3, [Warren 1999] Fig. 6.12.

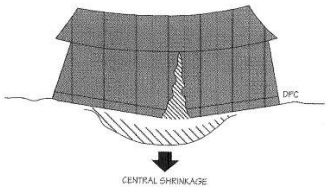
Damage pattern 24
Crack - in column or wall - vertical - tapered towards one end - widest at bottom

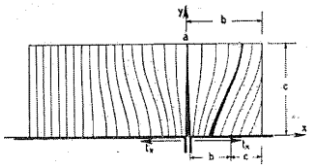
A. Damage pattern



symptoms:
- ■ S: crack
- ■ S: crack direction is vertical
- ■ S: crack is tapered towards one end
- ■ S: crack is widest at bottom, narrowest at top

context conditions included in pattern:
- ■ G: damage appears in column or wall





Examples. [Hinks and Cook 1997] Fig. 8.4, [Marshall et al. 2009] p.27, [Mastrodicasa 1993] Fig. 75.

B. Hypotheses

- ☐ 1.A Vertical settlement: mid-settlement / both-ends-heave
- ☐ 1.B Vertical settlement: one-end-settlement / one-end-heave
- ☐ 3.1.6 Hindered dimensional changes, temperature/moisture induced, difference in conditions between below and above ground

C. Essential conditions

For hypotheses and corresponding essential conditions of vertical settlement, see Part III of this tool.

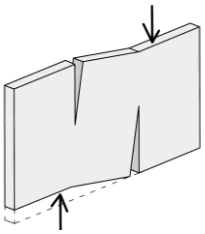
Additional symptom or context condition	**1.A**	**1.B**	**3.1.6**
G: absence of sufficient expansion joints	·	·	■

D. Further reading

[Hinks and Cook 1997] Fig. 8.4, [Hinks and Cook 1997] Fig. 8.7, [Marshall et al. 2009] p.27, [Mastrodicasa 1993] Fig. 75, [Naldini et al. 2007].

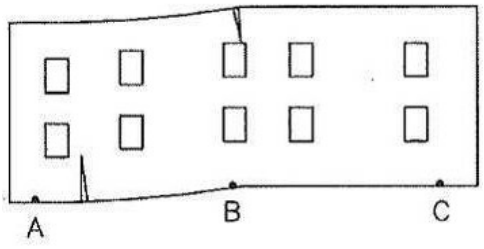
Damage pattern 25
Crack - in column or wall - vertical - tapered towards one end - one crack widest at top, one widest at bottom

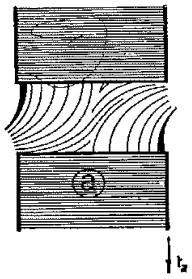
A. Damage pattern



symptoms:
- ■ S: crack
- ■ S: crack direction is vertical
- ■ S: crack is tapered towards one end
- ■ S: one crack is widest at top, narrowest at bottom
- ■ S: one crack is widest at bottom, narrowest at top

context conditions included in pattern:
- ■ G: damage appears in column or wall





Examples. [Croci 1998] Fig. 5.23, [Feilden 2003] Fig. 14.8, [Mastrodicasa 1993] Fig. 105 a..

B. Hypotheses

☐ 1.B Vertical settlement: one-end-settlement / one-end-heave

C. Essential conditions

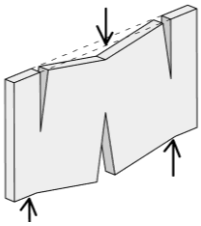
For hypotheses and corresponding essential conditions of vertical settlement, see Part III of this tool.

D. Further reading

[Croci 1998] Fig. 5.23, [Feilden 2003] Fig. 14.6, [Feilden 2003] Fig. 14.8, [Kastner et al. 2003] Fig. 5.3c, [Mastrodicasa 1993] Fig. 105 a.

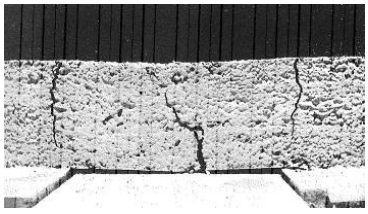
Damage pattern 26
Crack - in column or wall - vertical - tapered towards one end - two cracks widest at top, one at bottom

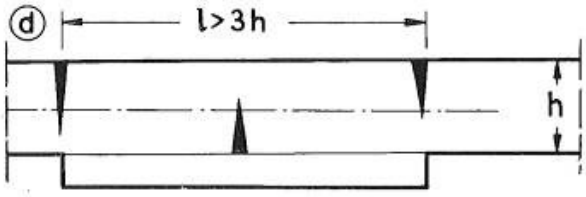
A. Damage pattern



symptoms:
- ■ S: crack
- ■ S: crack direction is vertical
- ■ S: crack is tapered towards one end
- ■ S: one crack is widest at bottom, narrowest at top
- ■ S: two cracks are widest at top, narrowest at bottom

context conditions included in pattern:
- ■ G: damage appears in column or wall





Examples. [Mastrodicasa 1993] Fot. 26, [Mastrodicasa 1993] Fig. 70 d.

B. Hypotheses

☐ 1.A Vertical settlement: mid-settlement / both-ends-heave

C. Essential conditions

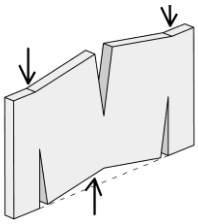
For hypotheses and corresponding essential conditions of vertical settlement, see Part III of this tool.

D. Further reading

[Mastrodicasa 1993] Fot. 26, [Mastrodicasa 1993] Fig. 70 d.

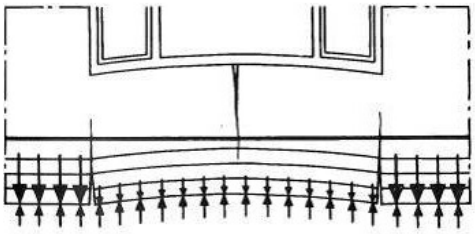
Damage pattern 27
Crack - in column or wall - vertical - tapered towards one end - one crack widest at top, two widest at bottom

A. Damage pattern



symptoms:
- ■ S: crack
- ■ S: crack direction is vertical
- ■ S: crack is tapered towards one end
- ■ S: one crack is widest at top, narrowest at bottom
- ■ S: two cracks are widest at bottom, narrowest at top

context conditions included in pattern:
- ■ G: damage appears in column or wall



Examples. [Bakker 1963] Fig. 21.

B. Hypotheses

☐ 1.C Vertical settlement: both-ends-settlement / mid-heave

C. Essential conditions

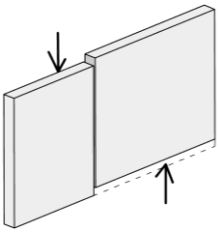
For hypotheses and corresponding essential conditions of vertical settlement, see Part III of this tool.

D. Further reading

[Bakker 1963] Fig. 21.

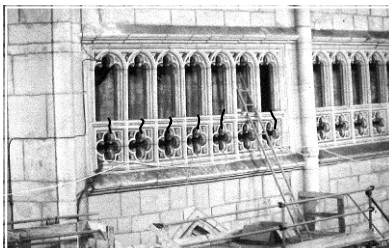
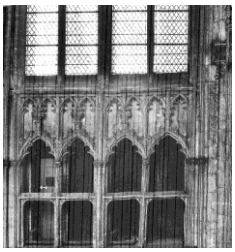
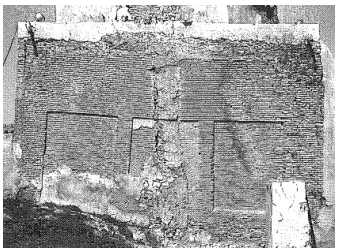
Damage pattern 28
Crack - in column or wall - vertical - constant size or tapered towards both ends - in-plane displacement, parallel to crack

A. Damage pattern



symptoms:
- ■ S: crack
- ■ S: crack direction is vertical
- ■ S: crack has constant size or is tapered towards both ends
- ■ S: in-plane displacement, parallel to crack

context conditions included in pattern:
- ■ G: damage appears in column or wall

Examples. [Croci 1998] Fig. 5.11, [Feilden 2003] Fig. 14.6, [Warren 1999] Fig. 6.5b.

B. Hypotheses

- ☐ 1.A Vertical settlement: mid-settlement / both-ends-heave
- ☐ 1.B Vertical settlement: one-end-settlement / one-end-heave

C. Essential conditions

For hypotheses and corresponding essential conditions of vertical settlement, see Part III of this tool.

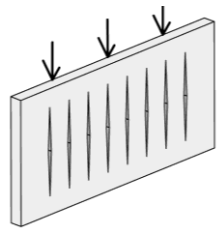
D. Further reading

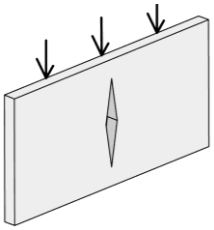
[Croci 1998] Fig. 5.11, [Feilden 2003] Fig. 14.6, [Warren 1999] Fig. 5.7, [Warren 1999] Fig. 6.5a, [Warren 1999] Fig. 6.5b.

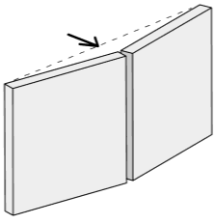
Damage pattern 29

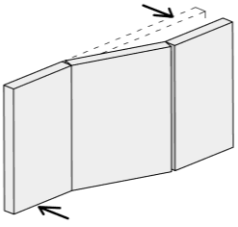
Crack - in column or wall - vertical - constant size or tapered towards both ends - in-plane displacement, perpendicular to crack

A. Damage pattern







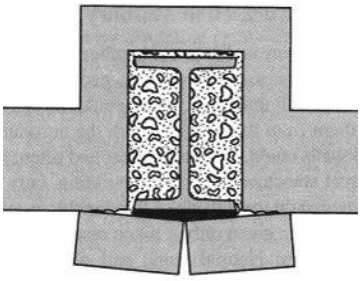


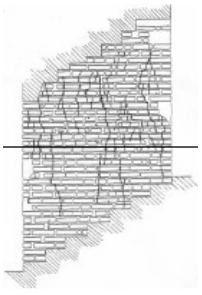
symptoms:

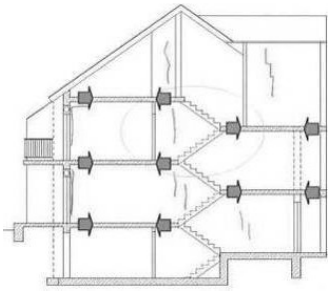
- S: crack
- S: crack direction is vertical
- S: crack has constant size or is tapered towards both ends
- S: in-plane displacement, perpendicular to crack

context conditions included in pattern:

- G: damage appears in column or wall







Examples. [Beckmann and Bowles 2004] fig. 6.13a, [Binda et al. 2000] Fig. 39, [Meichsner and Rohr-Suchalla 2008] Bild 205.

B. Hypotheses

- ☐ 1.D Horizontal soil movement
- ☐ 2.1.1 Overloading due to change in load, vertical, increase in self-weight, at time of construction
- ☐ 2.1.2 Overloading due to change in load, vertical, increase in self-weight, extensions built in or onto building
- ☐ 2.1.5 Overloading due to change in load, horizontal, thrust of arch, vault or dome
- ☐ 2.1.7 Overloading due to change in load, horizontal, thrust of roof truss
- ☐ 2.1.15 Overloading due to change in load, vibrational, natural or induced earthquake
- ☐ 2.1.16 Overloading due to change in load, vibrational, machinery or traffic
- ☐ 2.3.8 Overloading due to change in resistance, decrease in capacity of masonry, due to wetness
- ☐ 2.3.9 Overloading due to change in resistance, decrease in capacity of masonry, due to creep
- ☐ 3.1.1 Hindered dimensional changes, temperature/moisture induced, difference in behaviour between two types of units in masonry
- ☐ 3.1.3 Hindered dimensional changes, temperature/moisture induced, difference in behaviour between masonry and concrete
- ☐ 3.1.4 Hindered dimensional changes, temperature/moisture induced, difference in behaviour between masonry and timber
- ☐ 3.1.5 Hindered dimensional changes, temperature/moisture induced, difference in conditions between shady and sunny side
- ☐ 3.1.7 Hindered dimensional changes, temperature/moisture induced, difference in conditions between in-doors and out-of-doors
- ☐ 3.1.8 Hindered dimensional changes, temperature/moisture induced, abrupt extreme change in moisture content, irreversible shrinkage of unfired artificial stone after production
- ☐ 3.1.9 Hindered dimensional changes, temperature/moisture induced, abrupt extreme change in moisture content, irreversible swelling of fired clay bricks after production
- ☐ 3.3 Hindered dimensional changes, due to corrosion

C. Essential conditions

For hypotheses and corresponding essential conditions of horizontal settlement, see Part III of this tool.

Additional symptom or context condition		**1.D**	**2.1.1**	**2.1.2**	**2.1.5**	**2.1.7**
G:	damage appears at or just below the springings	·	·	·	■	·
G:	presence of arch, vault or dome adjacent to damaged area	·	·	·	■	·
G:	damage appears at or just below roof level	·	·	·	·	■
T:	damage has appeared after the following occurrence	·	·	■	·	·
G:	occurrence of extension built in or on top of existing building	·	·	■	·	·
T:	damage has appeared in the first years after construction	·	■	·	·	·

Additional symptom or context condition		2.1.15	2.1.16	2.3.8	2.3.9	3.1.1
S:	water stains	·	·	■	·	·
M:	presence of lime-based mortar	·	·	·	■	·
M:	damage appears at or near connection between two types of units	·	·	·	·	■
M:	presence of two types of units	·	·	·	·	■
E:	presence of source of moisture	·	·	■	·	·
G:	presence of high (gravity) load	·	·	·	■	·
G:	damage appears in zone at about two thirds of the height of the wall	·	·	·	■	·
T:	damage has appeared after the following occurrence	■	■	·	·	·
E:	occurrence of seismic event	■	·	·	·	·
E:	occurrence of vibrations with considerable amplitude, due to machinery or traffic	·	■	·	·	·
T:	damage has appeared gradually, over a considerable period of time	·	·	·	■	·

Additional symptom or context condition		3.1.3	3.1.4
M:	presence of a concrete floor slab	②	·
M:	presence of a concrete roof slab	③	·
M:	presence of a concrete lintel	⑥	·
M:	presence of timber beam	·	①
M:	presence of timber window frame	·	②
G:	damage appears with maximum halfway between two floors	②	·
G:	damage appears at or just below roof level	③	·
G:	damage appears next to and above lintel	⑥	·
G:	damage appears with maximum at or just below level of beam	·	①
G:	damage appears near an opening	·	②

Additional symptom or context condition		3.1.5	3.1.7	3.1.8	3.1.9	3.3
S:	rust stains	·	·	·	·	■
M:	damage appears in unfired artificial stone units	·	·	■	·	·
M:	damage appears in fired clay brick units	·	·	·	■	·
M:	presence of clay bricks that were freshly produced at time of construction	·	·	·	■	·
M:	damage appears at location of iron element	·	·	·	·	■
M:	presence of iron element embedded in masonry	·	·	·	·	■
G:	absence of sufficient expansion joints	■	■	·	·	·
G:	damage appears at corner	■	·	·	·	·
G:	damage appears at connection between internal and external wall	·	■	·	·	·
T:	damage has appeared in the first years after construction	·	·	■	■	·

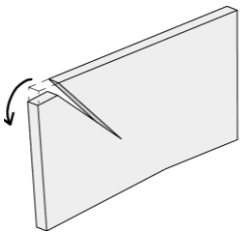
D. Further reading

[Beckmann and Bowles 2004] fig. 6.13a, [Binda et al. 2000] Fig. 39, [Cook and Hinks 1992] Fig. 9.6, [Croci 1998] Fig. 2.29 f, [Croci 1998] Fig. 2.32 a, [Douglas and Ransom 2007] Fig. 10.6, [Eldridge 1976] p. 94, [Eldridge 1976] p. 96, [Eldridge 1976] p. 100, [Eldridge 1976] p. 102, [Feilden 2003] Fig. 14.14a, [Harvey 2004] case 6, [Hendry and Khalaf 2001] Fig 7.2 a, [Hendry and Khalaf 2001] Fig. 7.2 b, [Hendry and Khalaf 2001] Fig 7.2 c, [Hinks and Cook 1997] Fig. 10.12, [Marshall et al. 2009] p. 41 d, [Marshall et al. 2009] p. 42 b, [Mastrodicasa 1993] Fig. 78a, b, [Mastrodicasa 1993]Fig. 110, [Mastrodicasa 1993] Fig. 115 a, [Mastrodicasa 1993] Fig. 116, [Mastrodicasa 1993] Fig. 117, [Mastrodicasa 1993] Fig .118, [Mastrodicasa 1993] Fig. 316 a, c, [Meichsner and Rohr-Suchalla 2008] Bild 187, [Meichsner and Rohr-Suchalla 2008] Bild 194, [Meichsner and Rohr-Suchalla 2008] Bild 205, [Meichsner and Rohr-Suchalla 2008] Bild 211, [Naldini

et al. 2007], [Onsiteformasonry et al. 2002] par. 7.2.13 POLIMI, [Pfefferkorn 1994] Bild 31, [Pfefferkorn 1994] Bild 85, [Pieper 1983] Bild 24.15 (detail), [Richardson 2001] plate 46, [Schubert 2009] case 2.1.3.1, [Schubert 2009] case 2.1.3.2, [Schubert 2009] case 2.2.2.1, [Schubert 2009] case 2.3.1.1, [Schubert 2009] case 2.3.1.2, [Schubert 2009] case 2.5.2, [Stichting Bouwresearch 1966] Fig. 21, [Stichting Bouwresearch 1966] Fig. 27, [Stichting Bouwresearch 1966] Fig. 76 d, e, [Stichting Bouwresearch 1976] p. 19, [van Stigt 1995], [TNO DIANA BV 2008] example Wall.

Damage pattern 30
Crack - in column or wall - diagonal, in one direction - tapered towards one end - widest at top - halfway the length

A. Damage pattern



symptoms:
- ■ S: crack
- ■ S: crack direction is diagonal
- ■ S: crack is tapered towards one end
- ■ S: crack is widest at top, narrowest at bottom

context conditions included in pattern:
- ■ G: damage appears in column or wall
- ■ G: damage appears with maximum halfway the length

Examples. [Eldridge 1976] p.118.

B. Hypotheses

☐ 1.C Vertical settlement: both-ends-settlement / mid-heave

C. Essential conditions

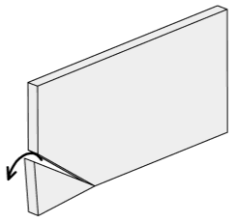
For hypotheses and corresponding essential conditions of vertical settlement, see Part III of this tool.

D. Further reading

[Eldridge 1976] p.118.

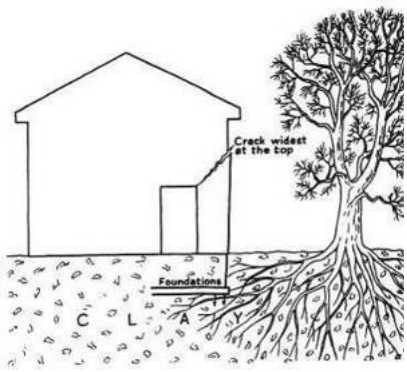
Damage pattern 31
Crack - in column or wall - diagonal, in one direction - tapered towards one end - widest at top - at a corner

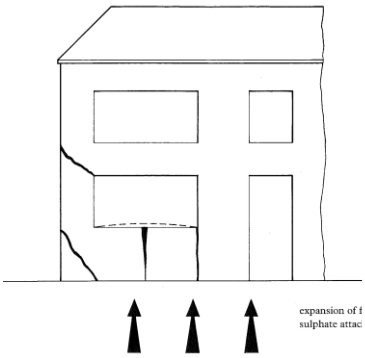
A. Damage pattern

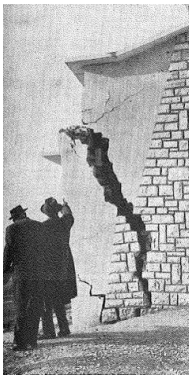


symptoms:
- ■ S: crack
- ■ S: crack direction is diagonal
- ■ S: crack is tapered towards one end
- ■ S: crack is widest at top, narrowest at bottom

context conditions included in pattern:
- ■ G: damage appears in column or wall
- ■ G: damage appears at a corner







Examples. [Douglas and Ransom 2007] fig. 8.1, [Eldridge 1976] p. 138, [Mastrodicasa 1993] Fot. 125.

B. Hypotheses

- ☐ 1.B Vertical settlement: one-end-settlement / one-end-heave
- ☐ 3.1.3 Hindered dimensional changes, temperature/moisture induced, difference in behaviour between masonry and concrete
- ☐ 3.1.5 Hindered dimensional changes, temperature/moisture induced, difference in conditions between shady and sunny side

C. Essential conditions

For hypotheses and corresponding essential conditions of vertical settlement, see Part III of this tool.

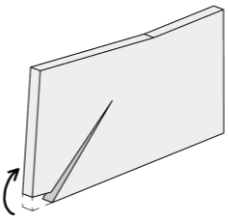
	Additional symptom or context condition	1.B	3.1.3	3.1.5
M:	presence of a concrete floor slab	·	■	·
G:	damage appears with maximum at or near floor level	·	■	·
G:	damage appears at corner	·	·	■
G:	absence of sufficient expansion joints	·	·	■

D. Further reading

[Ceci et al. 2010] Fig. 15a, [Cook and Hinks 1992] Fig. 6.4a, [Cook and Hinks 1992] Fig. 6.4b, [Douglas and Ransom 2007] fig. 8.1, [Eldridge 1976] p. 138, [Kastner et al. 2003] Fig. 4.5, [Kastner et al. 2003] Fig. 4.8, [Marshall et al. 2009] p. 17, [Marshall et al. 2009] p. 18, [Mastrodicasa 1993] Fot. 125, [Meichsner and Rohr-Suchalla 2008] Bild 182.

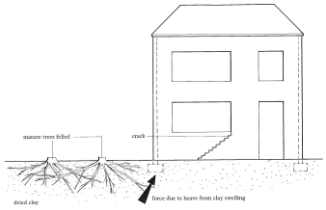
Damage pattern 32
Crack - in column or wall - diagonal, in one direction - tapered towards one end - widest at bottom

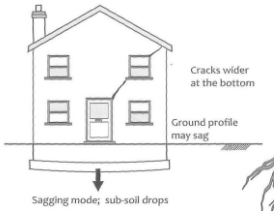
A. Damage pattern

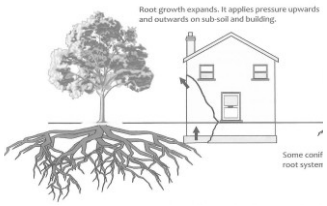


symptoms:
- ■ S: crack
- ■ S: crack direction is diagonal
- ■ S: crack is tapered towards one end
- ■ S: crack is widest at bottom, narrowest at top

context conditions included in pattern:
- ■ G: damage appears in column or wall







Examples. [Eldridge 1976] p. 109, [Marshall et al. 2009] p.18, [Marshall et al. 2009] p. 21.

B. Hypotheses

- ☐ 1.B Vertical settlement: one-end-settlement / one-end-heave
- ☐ 3.1.6 Hindered dimensional changes, temperature/moisture induced, difference in conditions between below and above ground

C. Essential conditions

For hypotheses and corresponding essential conditions of vertical settlement, see Part III of this tool.

Additional symptom or context condition	**1.B**	**3.1.6**
G: absence of sufficient expansion joints	·	■

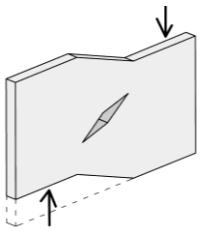
D. Further reading

[Eldridge 1976] p. 109, [Marshall et al. 2009] p.18, [Marshall et al. 2009] p. 21, [Marshall et al. 2009] p. 22, [Marshall et al. 2009] p. 24.

Damage pattern 33

Crack - in column or wall - diagonal, in one direction - constant size or tapered towards both ends - in-plane deformation with deviation from horizontal

A. Damage pattern

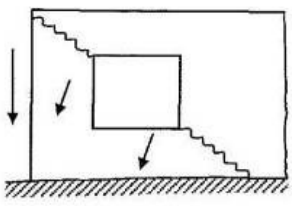


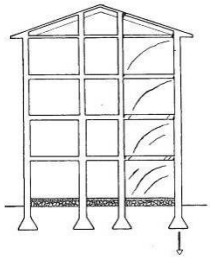
symptoms:

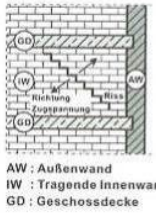
- ■ S: crack
- ■ S: crack direction is diagonal
- ■ S: crack has constant size or is tapered towards both ends
- ■ S: deformation
- ■ S: deformation in-plane
- ■ S: deviation from horizontal: bed joints are not horizontal anymore

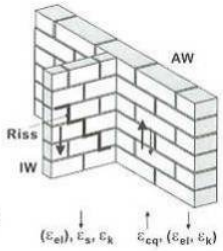
context conditions included in pattern:

- ■ G: damage appears in column or wall









Examples. [Hendry and Khalaf 2001] Fig. 7.3 c, [Mastrodicasa 1993] Fig. 304, [Schubert 2009] case 2.2.3.1.

B. Hypotheses

- ☐ 1.B Vertical settlement: one-end-settlement / one-end-heave
- ☐ 2.1.15 Overloading due to change in load, vibrational, natural or induced earthquake
- ☐ 2.1.16 Overloading due to change in load, vibrational, machinery or traffic
- ☐ 3.1.1 Hindered dimensional changes, temperature/moisture induced, difference in behaviour between two types of units in masonry

C. Essential conditions

For hypotheses and corresponding essential conditions of vertical settlement, see Part III of this tool.

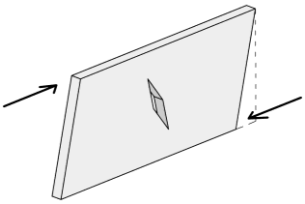
	Additional symptom or context condition	1.B	2.1.15	2.1.16	3.1.1
M:	damage appears at or near connection between two types of units	·	·	·	■
M:	presence of two types of units	·	·	·	■
T:	damage has appeared after the following occurrence	·	■	■	·
E:	occurrence of seismic event	·	■	·	·
E:	occurrence of vibrations with considerable amplitude, due to machinery or traffic	·	·	■	·

D. Further reading

[Croci 1998] Fig. 2.29 c, [Hendry and Khalaf 2001] Fig. 7.3 c, [Kastner et al. 2003] Fig. 3.2, [Mastrodicasa 1993] Fig 57 b, [Mastrodicasa 1993] Fig 71 c, [Mastrodicasa 1993] Fig. 105 b, [Mastrodicasa 1993] Fig. 304, [Meichsner and Rohr-Suchalla 2008] Bild 173, [Meichsner and Rohr-Suchalla 2008] Bild 174, [Meichsner and Rohr-Suchalla 2008] Bild 208, [Meichsner and Rohr-Suchalla 2008] Bild 177, [Meichsner and Rohr-Suchalla 2008] Bild 208, [Meichsner and Rohr-Suchalla 2008] Bild 210, [Naldini et al. 2007], [Pfefferkorn 1994] Bild 226, [Schubert 2009] case 2.2.3.1, [Stichting Bouwresearch 1966] Fig. 30.1, [Stichting Bouwresearch 1975] Foto 33, [Stichting Bouwresearch 1975] Foto 38, [van Stigt 1995].

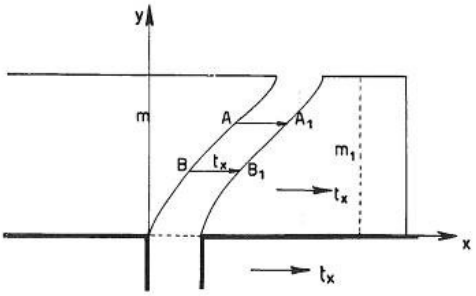
Damage pattern 34
Crack - in column or wall - diagonal, in one direction - constant size or tapered towards both ends - in-plane deformation with deviation from vertical

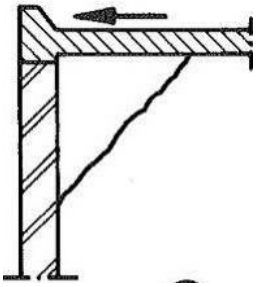
A. Damage pattern



symptoms:
- ■ S: crack
- ■ S: crack direction is diagonal
- ■ S: crack has constant size or is tapered towards both ends
- ■ S: deformation
- ■ S: deformation in-plane
- ■ S: deviation from vertical: vertical edge is not vertical anymore, out-of-plumb

context conditions included in pattern:
- ■ G: damage appears in column or wall





Examples. [Eldridge 1976] p. 112, [Mastrodicasa 1993] Fig 59, [Stichting Bouwresearch 1966] Fig. 30.2.

B. Hypotheses

- ☐ 2.1.5 Overloading due to change in load, horizontal, thrust of arch, vault or dome
- ☐ 2.1.7 Overloading due to change in load, horizontal, thrust of roof truss
- ☐ 2.1.15 Overloading due to change in load, vibrational, natural or induced earthquake
- ☐ 2.1.16 Overloading due to change in load, vibrational, machinery or traffic
- ☐ 2.2.7 Overloading due to change in load path, bending, of frame
- ☐ 3.1.3 Hindered dimensional changes, temperature/moisture induced, difference in behaviour between masonry and concrete
- ☐ 3.1.5 Hindered dimensional changes, temperature/moisture induced, difference in conditions between shady and sunny side
- ☐ 3.1.7 Hindered dimensional changes, temperature/moisture induced, difference in conditions between in-doors and out-of-doors

☐ 3.1.9 Hindered dimensional changes, temperature/moisture induced, abrupt extreme change in moisture content, irreversible swelling of fired clay bricks after production
☐ 3.2 Hindered dimensional changes, due to frost action
☐ 3.4.2 Hindered dimensional changes, due to salt attack, formation of swelling compounds

C. Essential conditions

Additional symptom or context condition		2.1.5	2.1.7	2.1.15	2.1.16	2.2.7
M:	presence of a concrete frame, with masonry used as infill	·	·	·	·	■
G:	damage appears at or just below the springings	■	·	·	·	·
G:	presence of arch, vault or dome adjacent to damaged area	■	·	·	·	·
G:	damage appears at or just below roof level	·	■	·	·	·
T:	damage has appeared after the following occurrence	·	·	■	■	·
E:	occurrence of seismic event	·	·	■	·	·
E:	occurrence of vibrations with considerable amplitude, due to machinery or traffic	·	·	·	■	·

Additional symptom or context condition		3.1.3	3.1.5	3.1.7
M:	presence of a concrete floor slab	①	·	·
M:	presence of a concrete roof slab	③	·	·
G:	damage appears with maximum at or near floor level	①	·	·
G:	damage appears at or just below roof level	③	·	·
G:	absence of sufficient expansion joints	·	■	■
G:	damage appears at corner	·	■	·
G:	damage appears at connection between internal and external wall	·	·	■

Additional symptom or context condition		3.1.9	3.2	3.4.2
S:	crack	·	■	·
S:	crack	·	·	■
S:	in-plane displacement, parallel to crack	·	·	■
M:	damage appears in fired clay brick units	■	·	·
M:	presence of clay bricks that were freshly produced at time of construction	■	·	·
M:	damage appears in joints	·	·	■
G:	damage appears in external building component	·	■	■
E:	presence of source of moisture	·	■	■
G:	damage appears at roof edge, in parapet wall	·	■	·
E:	presence of source of salt	·	·	■
E:	occurrence of temperatures below freezing point	·	■	·
T:	damage has appeared in the first years after construction	■	·	·

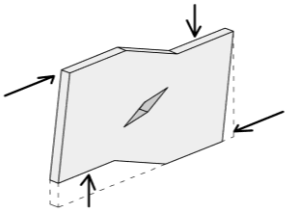
D. Further reading

[Eldridge 1976] p. 112, [Eldridge 1976] p. 152, [Hendry and Khalaf 2001] Fig. 7.4 a, [Mastrodicasa 1993] Fig 59, [Naldini et al. 2007], [Stichting Bouwresearch 1966] Fig. 30.2, [Stichting Bouwresearch 1966] Fig. 30.3, [Stichting Bouwresearch 1976] p. 53,[van Stigt 1995].

Damage pattern 35

Crack - in column or wall - diagonal, in one direction - constant size or tapered towards both ends - in-plane deformation with deviation from horizontal and from vertical

A. Damage pattern

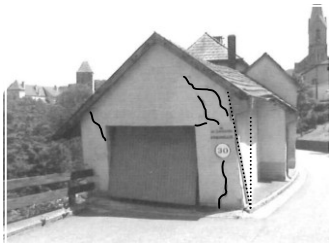


symptoms:

- ■ S: crack
- ■ S: crack direction is diagonal
- ■ S: crack has constant size or is tapered towards both ends
- ■ S: deformation
- ■ S: deformation in-plane
- ■ S: deviation from horizontal: bed joints are not horizontal anymore
- ■ S: deviation from vertical: vertical edge is notvertical anymore, out-of-plumb

context conditions included in pattern:

- ■ G: damage appears in column or wall



Examples. [Meichsner and Rohr-Suchalla 2008] Bild 175.

B. Hypotheses

☐ 1.B Vertical settlement: one-end-settlement / one-end-heave

C. Essential conditions

For hypotheses and corresponding essential conditions of vertical settlement, see Part III of this tool.

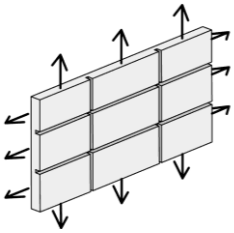
D. Further reading

[Meichsner and Rohr-Suchalla 2008] Bild 175.

Damage pattern 36

Crack - in column or wall - combination of directions - including horizontal crack(s) - horizontal plus vertical cracks - crack pattern

A. Damage pattern



symptoms:

- ■ S: crack
- ■ S: one crack of which crack direction is horizontal
- ■ S: one crack of which crack direction is vertical
- ■ S: crack pattern is # shaped

context conditions included in pattern:

- ■ G: damage appears in column or wall

Examples. [Naldini et al. 2007] Fig. 3.

B. Hypotheses

☐ 3.4.2 Hindered dimensional changes, due to salt attack, formation of swelling compounds

C. Essential conditions

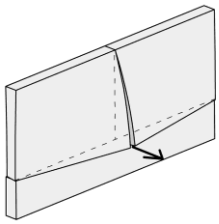
	Additional symptom or context condition	3.4.2
S:	in-plane displacement, parallel to crack	■
M:	damage appears in joints	■
S:	crack	■
G:	damage appears in external building component	■
E:	presence of source of moisture	■
E:	presence of source of salt	■

D. Further reading

[Naldini et al. 2007] Fig. 3.

Damage pattern 37
Crack - in column or wall - combination of directions - including horizontal crack(s) - horizontal plus vertical cracks - crack pattern ⊥

A. Damage pattern

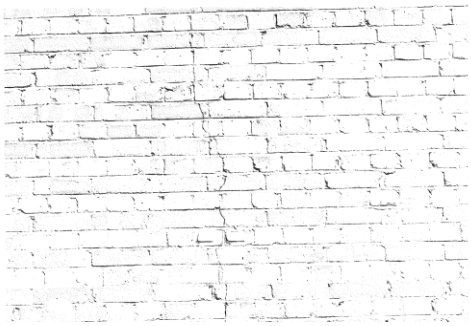


symptoms:

- ■ S: crack
- ■ S: one crack of which crack direction is horizontal; crack has constant size or is tapered towards both ends
- ■ S: one crack of which crack direction is vertical; crack is tapered towards one end; crack is widest at bottom, narrowest at top
- ■ S: crack pattern is ⊥ shaped

context conditions included in pattern:

- ■ G: damage appears in column or wall



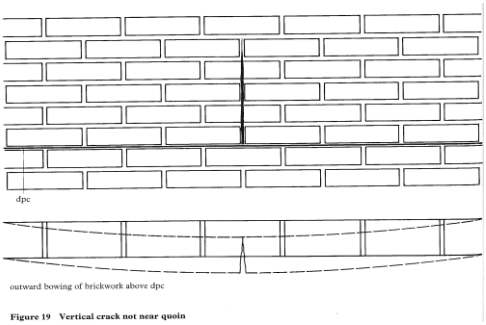


Figure 19 Vertical crack not near quoin

Examples. [Eldridge 1976] p. 91

B. Hypotheses

☐ 3.1.9 Hindered dimensional changes, temperature/moisture induced, abrupt extreme change in moisture content, irreversible swelling of fired clay bricks after production

C. Essential conditions

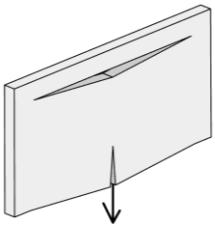
Additional symptom or context condition		3.1.9
M:	damage appears in fired clay brick units	■
M:	presence of clay bricks that were freshly produced at time of construction	■
T:	damage has appeared in the first years after construction	■

D. Further reading

[Eldridge 1976] p. 91

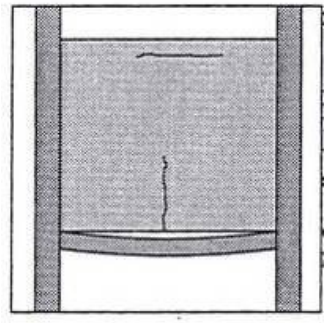
Damage pattern 38
Crack - in column or wall - combination of directions - including horizontal crack(s) - horizontal plus vertical cracks - crack pattern T

A. Damage pattern



symptoms:
- ■ S: crack
- ■ S: one crack of which crack direction is horizontal; crack has constant size or is tapered towards both ends
- ■ S: one crack of which crack direction is vertical; crack is tapered towards one end; crack is widest at bottom, narrowest at top
- ■ S: crack pattern is T shaped

context conditions included in pattern:
- ■ G: damage appears in column or wall



Examples. [van Stigt 1995].

B. Hypotheses

☐ 2.2.6 Overloading due to change in load path, bending, of floor that supports damaged wall

C. Essential conditions

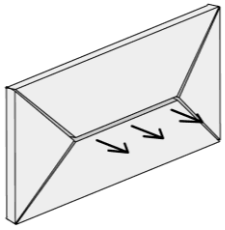
Additional symptom or context condition	**2.2.6**
G: damage appears in wall that is supported by floor	■

D. Further reading

[van Stigt 1995].

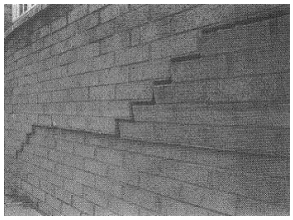
Damage pattern 39
Crack - in column or wall - combination of directions - including horizontal crack(s) - horizontal plus diagonal cracks - crack pattern >---<

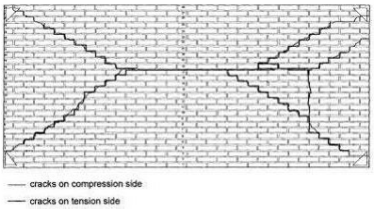
A. Damage pattern



symptoms:
- ■ S: crack
- ■ S: one crack of which crack direction is horizontal
- ■ S: four cracks of which crack direction is diagonal
- ■ S: crack pattern is >---< shaped
- ■ S: deformation
- ■ S: deformation out-of-plane

context conditions included in pattern:
- ■ G: damage appears in column or wall





Examples. [Hinks and Cook 1997] Fig. 10.1, [Onsiteformasonry et al. 2002] par. 7.6.1 ZAG, [van der Pluijm 2000] Fig. 11.

B. Hypotheses

- ☐ 2.1.4 Overloading due to change in load, horizontal, push of wind
- ☐ 2.1.9 Overloading due to change in load, horizontal, push of retained earth
- ☐ 2.1.12 Overloading due to change in load, horizontal, impact of frontal collision
- ☐ 2.1.13 Overloading due to change in load, horizontal, impact of internal explosion
- ☐ 3.1.3 Hindered dimensional changes, temperature/moisture induced, difference in behaviour between masonry and concrete

C. Essential conditions

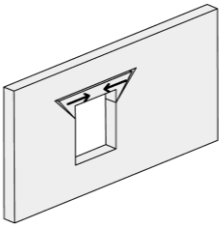
Additional symptom or context condition		2.1.4	2.1.9	2.1.12	2.1.13	3.1.3
S:	deformation out-of-plane, inward	·	·	■	·	·
S:	deformation out-of-plane, outward	·	·	·	■	·
M:	presence of a concrete floor slab	·	·	·	·	■
G:	damage appears in external building component	■	·	■	·	·
G:	damage appears in retaining wall	·	■	·	·	·
G:	damage appears with maximum at or near floor level	·	·	·	·	■
T:	damage has appeared after the following occurrence	·	·	■	■	·
E:	occurrence of collision into the building	·	·	■	·	·
E:	occurrence of internal explosion	·	·	·	■	·

D. Further reading

[Hinks and Cook 1997] Fig. 10.1, [Onsiteformasonry et al. 2002] par. 7.6.1 ZAG, [van der Pluijm 2000] Fig. 11.

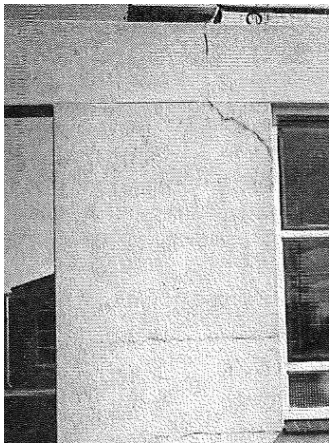
Damage pattern 40
Crack - in column or wall - combination of directions - including horizontal crack(s) - horizontal plus diagonal cracks - crack pattern \---/

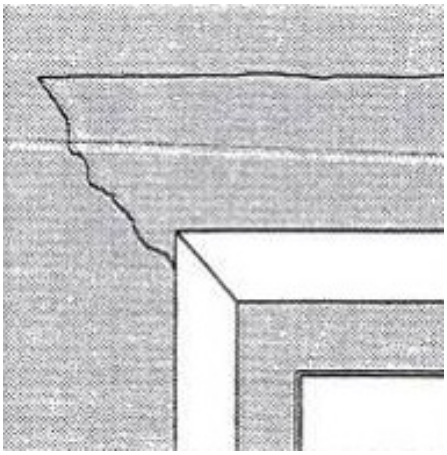
A. Damage pattern



symptoms:
- ■ S: crack
- ■ S: one crack of which crack direction is horizontal
- ■ S: two cracks of which crack direction is diagonal
- ■ S: crack pattern is \ --- / shaped

context conditions included in pattern:
- ■ G: damage appears in column or wall





Examples. [Bakker 1963] Fig. 165, [van Stigt 1995].

B. Hypotheses

☐ 3.1.3 Hindered dimensional changes, temperature/moisture induced, difference in behaviour between masonry and concrete

C. Essential conditions

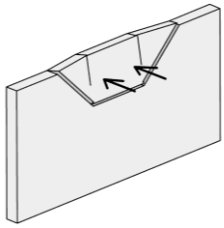
Additional symptom or context condition	**3.1.3**
M: presence of a concrete floor slab	■
G: damage appears next to and above lintel	■

D. Further reading

[Bakker 1963] Fig. 165, [van Stigt 1995].

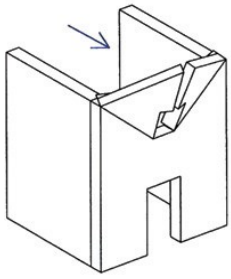
Damage pattern 41
Crack - in column or wall - combination of directions - including horizontal crack(s) - horizontal plus vertical plus diagonal cracks, crack pattern \|---|/

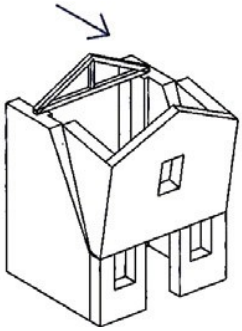
A. Damage pattern



symptoms:
- ■ S: crack
- ■ S: one crack of which crack direction is horizontal
- ■ S: wo cracks of which crack direction is vertical
- ■ S: two cracks of which crack direction is diagonal
- ■ S: crack pattern is \|---|/ shaped
- ■ S: deformation
- ■ S: deformation out-of-plane
- ■ S: deformation out-of-plane, outward

context conditions included in pattern:
- ■ G: damage appears in column or wall





Examples. [Protezione Civile 2006], [Protezione Civile 2006].

B. Hypotheses

- ☐ 2.1.5 Overloading due to change in load, horizontal, thrust of arch, vault or dome
- ☐ 2.1.7 Overloading due to change in load, horizontal, thrust of roof truss
- ☐ 2.1.9 Overloading due to change in load, horizontal, push of retained earth
- ☐ 2.1.15 Overloading due to change in load, vibrational, natural or induced earthquake
- ☐ 2.1.16 Overloading due to change in load, vibrational, machinery or traffic

C. Essential conditions

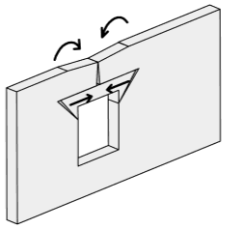
Additional symptom or context condition		2.1.5	2.1.7	2.1.9	2.1.15	2.1.16
G:	presence of arch, vault or dome adjacent to damaged area	■	·	·	·	·
G:	damage appears at or just below the springings	■	·	·	·	·
G:	damage appears at or just below roof level	·	■	·	·	·
G:	damage appears in retaining wall	·	·	■	·	·
T:	damage has appeared after the following occurrence	·	·	·	■	■
E:	occurrence of seismic event	·	·	·	■	·
E:	occurrence of vibrations with considerable amplitude, due to machinery or traffic	·	·	·	·	■

D. Further reading

[Mastrodicasa 1993] Fig. 128, [Mastrodicasa 1993] Fig. 129, [Mastrodicasa 1993] Fig. 139, [Protezione Civile 2006].

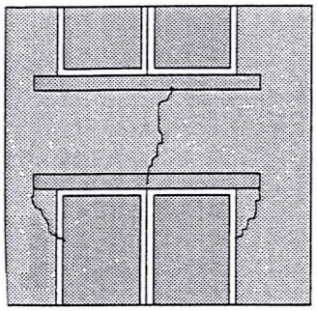
Damage pattern 42
Crack - in column or wall - combination of directions - no horizontal cracks - vertical plus diagonal cracks - crack pattern \ | /

A. Damage pattern



symptoms:
- ■ S: crack
- ■ S: one crack of which crack direction is vertical; crack is tapered towards one end; crack is widest at top, narrowest at bottom
- ■ S: two cracks of which crack direction is diagonal; crack has constant size or is tapered towards both ends
- ■ S: crack pattern is \ | / shaped

context conditions included in pattern:
- ■ G: damage appears in column or wall



Examples. [Naldini et al. 2007], [van Stigt 1995].

B. Hypotheses

☐ 3.1.3 Hindered dimensional changes, temperature/moisture induced, difference in behaviour between masonry and concrete

C. Essential conditions

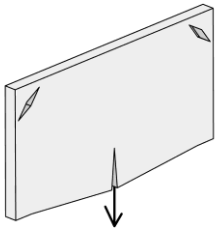
Additional symptom or context condition	**3.1.3**
M: presence of a concrete lintel	■
G: damage appears next to and above lintel	■

D. Further reading

[Naldini et al. 2007], [van Stigt 1995].

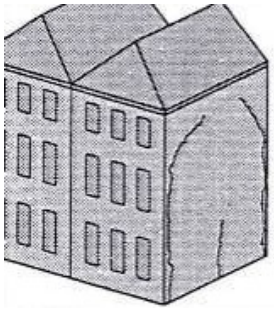
Damage pattern 43
Crack - in column or wall - combination of directions - no horizontal cracks - vertical plus diagonal cracks - crack pattern /| \

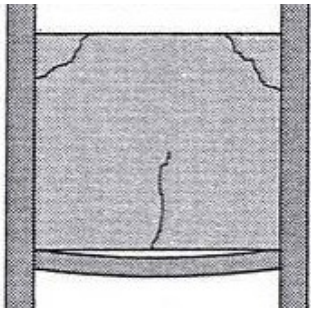
A. Damage pattern



symptoms:
- ■ S: crack
- ■ S: one crack of which crack direction is vertical; crack is tapered towards one end; crack is widest at bottom, narrowest at top
- ■ S: two cracks of which crack direction is diagonal; crack has constant size or is tapered towards both ends
- ■ S: crack pattern is / | \ shaped

context conditions included in pattern:
- ■ G: damage appears in column or wall





Examples. [van Stigt 1995], [van Stigt 1995].

B. Hypotheses

- ☐ 1.A Vertical settlement: mid-settlement / both-ends-heave
- ☐ 2.2.6 Overloading due to change in load path, bending, of floor that supports damaged wall

C. Essential conditions

For hypotheses and corresponding essential conditions of vertical settlement, see Part III of this tool.

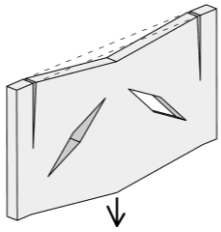
Additional symptom or context condition	**1.A**	**2.2.6**
G: damage appears in wall that is supported by floor	·	■

D. Further reading

[van Stigt 1995].

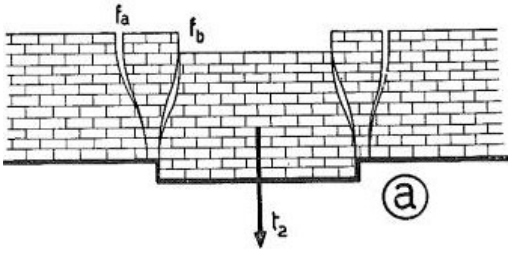
Damage pattern 44
Crack - in column or wall - combination of directions - no horizontal cracks - vertical plus diagonal cracks - crack pattern |/ \|

A. Damage pattern



symptoms:
- ■ S: crack
- ■ S: two cracks of which crack direction is vertical; crack is tapered towards one end; crack is widest at top, narrowest at bottom
- ■ S: two cracks of which crack direction is diagonal
- ■ S: crack pattern is | / \ | shaped

context conditions included in pattern:
- ■ G: damage appears in column or wall



Examples. [Mastrodicasa 1993]Fig. 97 a, b.

B. Hypotheses

☐ 1.A Vertical settlement: mid-settlement / both-ends-heave

C. Essential conditions

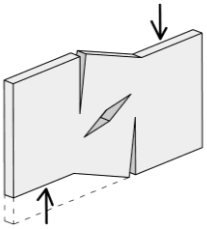
For hypotheses and corresponding essential conditions of vertical settlement, see Part III of this tool.

D. Further reading

[Mastrodicasa 1993]Fig. 97 a, b.

Damage pattern 45
Crack - in column or wall - combination of directions - no horizontal cracks - vertical plus diagonal cracks - crack pattern | / |

A. Damage pattern

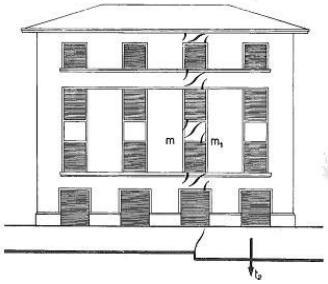


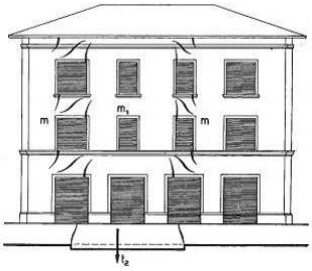
symptoms:

- ■ S: crack
- ■ S: one crack of which crack direction is vertical; crack is tapered towards one end; crack is widest at top, narrowest at bottom
- ■ S: one crack of which crack direction is vertical; crack is tapered towards one end; crack is widest at bottom, narrowest at top
- ■ S: one crack of which crack direction is diagonal; crack has constant size or is tapered towards both ends
- ■ S: crack pattern is | / | shaped

context conditions included in pattern:

- ■ G: damage appears in column or wall





Examples. [Mastrodicasa 1993] Fig. 105 c, [Mastrodicasa 1993]Fig. 106, [Mastrodicasa 1993]Fig. 107.

B. Hypotheses

☐ 1.B Vertical settlement: one-end-settlement / one-end-heave

C. Essential conditions

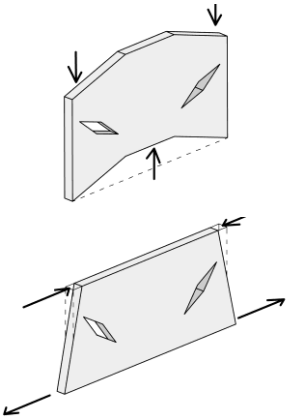
For hypotheses and corresponding essential conditions of vertical settlement, see Part III of this tool.

D. Further reading

[Mastrodicasa 1993] Fig. 105 c, [Mastrodicasa 1993]Fig. 106, [Mastrodicasa 1993]Fig. 107.

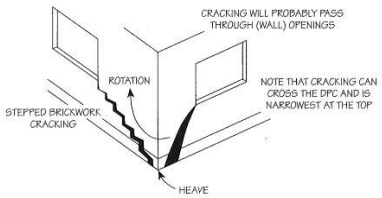
Damage pattern 46
Crack - in column or wall - combination of directions - no horizontal cracks - diagonal plus diagonal cracks, in two directions - crack pattern \/

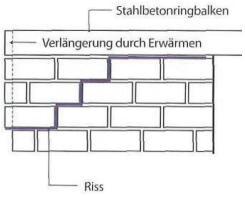
A. Damage pattern

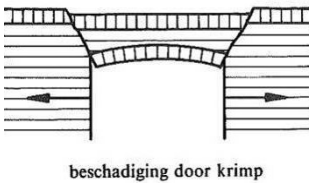


symptoms:
- ■ S: crack
- ■ S: two cracks
- ■ S: crack direction is diagonal
- ■ S: crack pattern is \ / shaped

context conditions included in pattern:
- ■ G: damage appears in column or wall







Examples. [Hinks and Cook 1997] Fig. 8.2, [Schubert 2009] case 2.1.2.1, [Stichting Bouwresearch 1966] Fig. 76 c.

B. Hypotheses

- ☐ 1.B Vertical settlement: one-end-settlement / one-end-heave
- ☐ 1.C Vertical settlement: both-ends-settlement / mid-heave
- ☐ 2.1.5 Overloading due to change in load, horizontal, thrust of arch, vault or dome
- ☐ 2.1.7 Overloading due to change in load, horizontal, thrust of roof truss
- ☐ 2.1.15 Overloading due to change in load, vibrational, natural or induced earthquake
- ☐ 2.1.16 Overloading due to change in load, vibrational, machinery or traffic
- ☐ 2.2.6 Overloading due to change in load path, bending, of floor that supports damaged wall
- ☐ 3.1.3 Hindered dimensional changes, temperature/moisture induced, difference in behaviour between masonry and concrete

☐ 3.1.5 Hindered dimensional changes, temperature/moisture induced, difference in conditions between shady and sunny side
☐ 3.1.8 Hindered dimensional changes, temperature/moisture induced, abrupt extreme change in moisture content, irreversible shrinkage of unfired artificial stone after production
☐ 3.3 Hindered dimensional changes, due to corrosion

C. Essential conditions

For hypotheses and corresponding essential conditions of vertical settlement, see Part III of this tool.

Additional symptom or context condition	1.B	1.C	2.1.5	2.1.7	2.1.15
G: damage appears at or just below the springings	·	·	■	·	·
G: presence of arch, vault or dome adjacent to damaged area	·	·	■	·	·
G: damage appears at or just below roof level	·	·	·	■	·
T: damage has appeared after the following occurrence	·	·	·	·	■
E: occurrence of seismic event	·	·	·	·	■

Additional symptom or context condition	2.1.16	2.2.6	3.1.3	3.1.5	3.1.8
M: presence of a concrete beam	·	·	■	·	·
M: presence of a concrete lintel	·	·	■	·	·
M: damage appears in unfired artificial stone units	·	·	·	·	■
G: damage appears in wall that is supported by floor	·	■	·	·	·
G: damage appears next to and above lintel	·	·	■	·	·
G: damage appears with maximum at or just below level of beam	·	·	■	·	·
G: absence of sufficient expansion joints	·	·	·	■	·
G: damage appears at corner	·	·	·	■	·
T: damage has appeared after the following occurrence	■	·	·	·	·
E: occurrence of vibrations with considerable amplitude, due to machinery or traffic	■	·	·	·	·
T: damage has appeared in the first years after construction	·	·	·	·	■

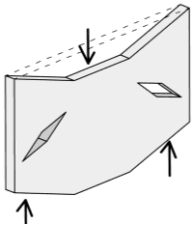
Additional symptom or context condition	3.3
S: rust stains	■
M: damage appears at location of iron element	■
M: presence of iron element embedded in masonry	■

D. Further reading

[Bakker 1963] Fig. 43, [Croci 1998] Fig. 5.10 b2, [Feilden 2003] Fig. 14.14b, [Hinks and Cook 1997] Fig. 8.2, [Hinks and Cook 1997] Fig. 10.14b, [Kastner et al. 2003] Fig. 2.2, [Meichsner and Rohr-Suchalla 2008] Bild 216, [Meichsner and Rohr-Suchalla 2008] Bild 217, [Pfefferkorn 1994] Bild 29, [Schubert 2009] case 2.1.2.1, [Stichting Bouwresearch 1976] p. 37.1, [Stichting Bouwresearch 1966] Fig. 76 c, [van Stigt 1995], [Warren 1999] Fig. 6.9.

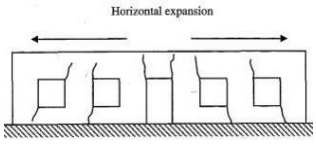
Damage pattern 47
Crack - in column or wall - combination of directions - no horizontal cracks - diagonal plus diagonal cracks, in two directions - crack pattern /\ - halfway the length

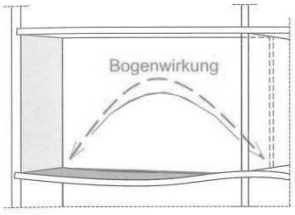
A. Damage pattern

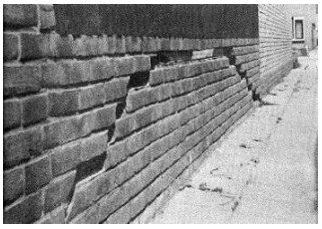


symptoms:
- ■ S: crack
- ■ S: two cracks
- ■ S: crack direction is diagonal
- ■ S: crack pattern is / \ shaped

context conditions included in pattern:
- ■ G: damage appears in column or wall
- ■ G: damage appears with maximum halfway the length







Examples. [Hendry and Khalaf 2001] Fig 7.1 c, [Meichsner and Rohr-Suchalla 2008] Bild 221, [Stichting Bouwresearch 1975] Foto 24.

B. Hypotheses

- ☐ 1.A Vertical settlement: mid-settlement / both-ends-heave
- ☐ 2.2.6 Overloading due to change in load path, bending, of floor that supports damaged wall
- ☐ 2.2.8 Overloading due to change in load path, bending, of lintel
- ☐ 2.3.1 Overloading due to change in resistance, geometrical discontinuities near opening
- ☐ 2.3.2 Overloading due to change in resistance, geometrical discontinuities below beam
- ☐ 3.1.1 Hindered dimensional changes, temperature/moisture induced, difference in behaviour between two types of units in masonry
- ☐ 3.1.3 Hindered dimensional changes, temperature/moisture induced, difference in behaviour between masonry and concrete
- ☐ 3.1.9 Hindered dimensional changes, temperature/moisture induced, abrupt extreme change in moisture content, irreversible swelling of fired clay bricks after production

C. Essential conditions

For hypotheses and corresponding essential conditions of vertical settlement, see Part III of this tool.

Additional symptom or context condition	1.A	2.2.6	2.2.8	2.3.1	2.3.2
G: damage appears in wall that is supported by floor	·	■	·	·	·
G: damage appears next to and above lintel	·	·	■	·	·
G: damage appears near an opening	·	·	·	■	·
G: damage appears with maximum at or just below level of beam	·	·	·	·	■

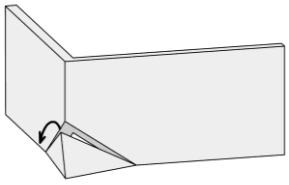
Additional symptom or context condition	3.1.1	3.1.3	3.1.9
M: damage appears at or near connection between two types of units	■	·	·
M: presence of two types of units	■	·	·
M: presence of a concrete roof slab	·	③	·
M: presence of a concrete lintel	·	⑥	·
M: damage appears in fired clay brick units	·	·	■
M: presence of clay bricks that were freshly produced at time of construction	·	·	■
G: damage appears at or just below roof level	·	③	·
G: damage appears next to and above lintel	·	⑥	·
T: damage has appeared in the first years after construction	·	·	■

D. Further reading

[Cook and Hinks 1992] Fig. 3.2b, [Croci 1998] Fig. 2.29 d, [Croci 1998] Fig. 2.29 h, [Croci 1998] Fig. 5.10 a, [Feilden 2003] Fig. 14.14d, [Hendry and Khalaf 2001] Fig 7.1 c, [Hendry and Khalaf 2001] Fig. 7.3 b, [Hendry and Khalaf 2001] Fig. 7.4 b, [Marshall et al. 2009] p. 44 a, b, [Marshall et al. 2009] p. 44 c, [Mastrodicasa 1993] Fig. 70b, [Mastrodicasa 1993] Fot. 27, [Mastrodicasa 1993] Fig. 305, [Meichsner and Rohr-Suchalla 2008] Bild 176, [Meichsner and Rohr-Suchalla 2008] Bild 212, [Meichsner and Rohr-Suchalla 2008] Bild 215, [Meichsner and Rohr-Suchalla 2008] Bild 221, [Naldini et al. 2007], [Pfefferkorn 1994] Bild 15, [Pfefferkorn 1994] Bild 105, [Pfefferkorn 1994] Bild 109, [Pfefferkorn 1994] Bild 207, [Schubert 2009] case 2.1.2.2, [Schubert 2009] case 2.2.3.1, [Schubert 2009] case 2.3.3.2, [Stichting Bouwresearch 1966] Fig. 10, [Stichting Bouwresearch 1975] Foto 9, [Stichting Bouwresearch 1975] Foto 24, [Stichting Bouwresearch 1976] p. 37.3, [van Stigt 1995].

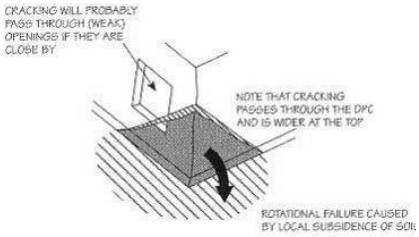
Damage pattern 48
Crack - in column or wall - combination of directions - no horizontal cracks - diagonal plus diagonal cracks, in two directions - crack pattern /\ - at a corner

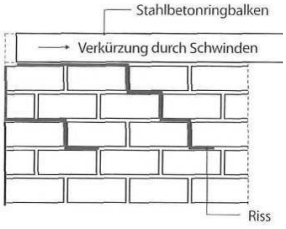
A. Damage pattern



symptoms:
- ■ S: crack
- ■ S: two cracks
- ■ S: crack direction is diagonal
- ■ S: crack pattern is / \ shaped
- ■ S: crack is tapered towards one end
- ■ S: crack is widest at top, narrowest at bottom

context conditions included in pattern:
- ■ G: damage appears in column or wall
- ■ G: damage appears at a corner





Examples. [Hinks and Cook 1997] Fig. 8.8c, [Meichsner and Rohr-Suchalla 2008] Bild 203, [Schubert 2009] case 2.1.2.1.

B. Hypotheses

- ☐ 1.B Vertical settlement: one-end-settlement / one-end-heave
- ☐ 2.2.6 Overloading due to change in load path, bending, of floor that supports damaged wall
- ☐ 3.1.3 Hindered dimensional changes, temperature/moisture induced, difference in behaviour between masonry and concrete
- ☐ 3.1.7 Hindered dimensional changes, temperature/moisture induced, difference in conditions between in-doors and out-of-doors

C. Essential conditions

For hypotheses and corresponding essential conditions of vertical settlement, see Part III of this tool.

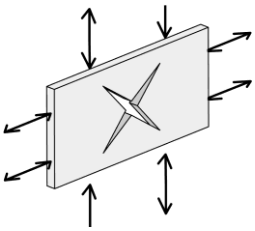
	Additional symptom or context condition	1.B	2.2.6	3.1.3	3.1.7
M:	presence of a concrete beam	·	·	■	·
G:	damage appears in wall that is supported by floor	·	■	·	·
G:	damage appears with maximum at or just below level of beam	·	·	■	·
G:	absence of sufficient expansion joints	·	·	·	■
G:	damage appears at connection between internal and external wall	·	·	·	■

D. Further reading

[Eldridge 1976] p. 106, [Hinks and Cook 1997] Fig. 8.8c, [Marshall et al. 2009] p. 18, [Marshall et al. 2009] p. 20, [Marshall et al. 2009] p. 24, [Meichsner and Rohr-Suchalla 2008] Bild 202, [Meichsner and Rohr-Suchalla 2008] Bild 203, [Pfefferkorn 1994] Bild 25, [Naldini et al. 2007], [Schubert 2009] case 2.1.2.1.

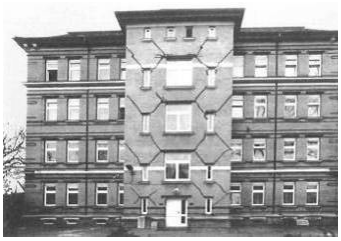
Damage pattern 49
Crack - in column or wall - combination of directions - no horizontal cracks - diagonal plus diagonal cracks, in two directions - crack pattern X

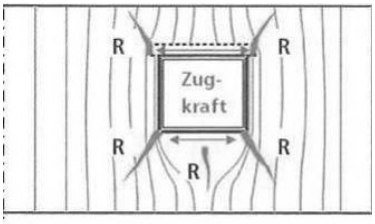
A. Damage pattern

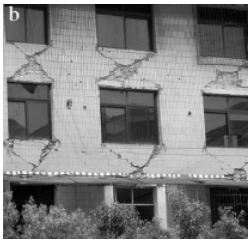


symptoms:
- ■ S: crack
- ■ S: two cracks
- ■ S: crack direction is diagonal
- ■ S: crack pattern is X shaped

context conditions included in pattern:
- ■ G: damage appears in column or wall







Examples. [Meichsner and Rohr-Suchalla 2008] Bild 216, [Schubert 2009] case 2.1.2.2, [Zhao et al. 2009] Fig. 12b.

B. Hypotheses

- ☐ 2.1.15 Overloading due to change in load, vibrational, natural or induced earthquake
- ☐ 2.1.16 Overloading due to change in load, vibrational, machinery or traffic
- ☐ 2.3.1 Overloading due to change in resistance, geometrical discontinuities near opening
- ☐ 3.3 Hindered dimensional changes, due to corrosion

C. Essential conditions

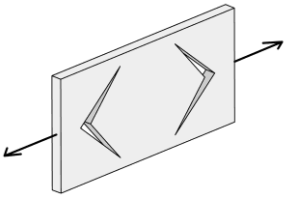
	Additional symptom or context condition	2.1.15	2.1.16	2.3.1	3.3
S:	rust stains	·	·	·	■
M:	damage appears at location of iron element	·	·	·	■
M:	presence of iron element embedded in masonry	·	·	·	■
G:	damage appears near an opening	·	·	■	·
T:	damage has appeared after the following occurrence	■	■	·	·
E:	occurrence of seismic event	■	·	·	·
E:	occurrence of vibrations with considerable amplitude, due to machinery or traffic	·	■	·	·

D. Further reading

[Ceci et al. 2010] Fig, 20b, [Croci 1998] Fig. 2.29 e, [Croci 1998] Fig. 2.29 i, [Croci 1998] Fig. 2.29 j, [Croci 1998] Fig. 6.34, [Croci 1998] Fig. 6.36, [Meichsner and Rohr-Suchalla 2008] Bild 216, [Meichsner and Rohr-Suchalla 2008] Bild 217, [Naldini et al. 2007], [Protezione Civile 2006], [Schubert 2009] case 2.1.2.2, [Zhao et al. 2009] Fig. 12a, [Zhao et al. 2009] Fig. 12b, [Zhao et al. 2009] Fig. 12c.

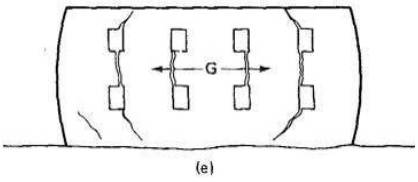
Damage pattern 50
Crack - in column or wall - combination of directions - no horizontal cracks - diagonal plus diagonal cracks, in two directions - crack pattern >

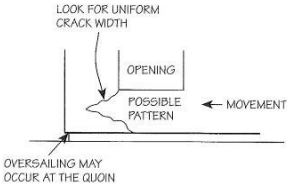
A. Damage pattern

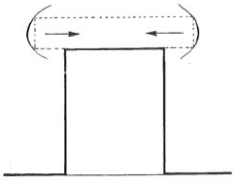


symptoms:
- ■ S: crack
- ■ S: crack direction is diagonal
- ■ S: crack pattern is > shaped

context conditions included in pattern:
- ■ G: damage appears in column or wall







Examples. [Feilden 2003] Fig. 14.14e, [Hinks and Cook 1997] Fig. 10.9 b1, [Mastrodicasa 1993] Fig. 317.

B. Hypotheses

- ☐ 1.D Horizontal soil movement
- ☐ 2.1.15 Overloading due to change in load, vibrational, natural or induced earthquake
- ☐ 2.1.16 Overloading due to change in load, vibrational, machinery or traffic
- ☐ 3.1.3 Hindered dimensional changes, temperature/moisture induced, difference in behaviour between masonry and concrete
- ☐ 3.1.6 Hindered dimensional changes, temperature/moisture induced, difference in conditions between below and above ground
- ☐ 3.1.8 Hindered dimensional changes, temperature/moisture induced, abrupt extreme change in moisture content, irreversible shrinkage of unfired artificial stone after production
- ☐ 3.1.9 Hindered dimensional changes, temperature/moisture induced, abrupt extreme change in moisture content, irreversible swelling of fired clay bricks after production
- ☐ 3.1.11 Hindered dimensional changes, temperature/moisture induced, lack of flexibility to accommodate movement

C. Essential conditions

For hypotheses and corresponding essential conditions of horizontal settlement, see Part III of this tool.

	Additional symptom or context condition	1.D	2.1.15	2.1.16	3.1.3	3.1.6
S:	crack is widest at bottom, narrowest at top	·	·	·	·	■
M:	presence of a concrete frame, with masonry used as infill	·	·	·	⑤	·
M:	presence of a concrete roof slab	·	·	·	③	·
M:	presence of a concrete lintel	·	·	·	⑥	·
G:	damage appears at or just below roof level	·	·	·	③	·
G:	damage appears next to and above lintel	·	·	·	⑥	·
G:	absence of sufficient expansion joints	·	·	·	·	■
T:	damage has appeared after the following occurrence	·	■	■	·	·
E:	occurrence of seismic event	·	■	·	·	·
E:	occurrence of vibrations with considerable amplitude, due to machinery or traffic	·	·	■	·	·

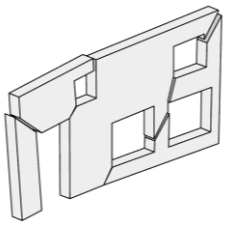
	Additional symptom or context condition	3.1.8	3.1.9	3.1.11
M:	damage appears in unfired artificial stone units	■	·	·
M:	damage appears in fired clay brick units	·	■	·
M:	presence of clay bricks that were freshly produced at time of construction	·	■	·
G:	damage appears near an opening	·	·	■
G:	absence of sufficient expansion joints	·	·	■
T:	damage has appeared in the first years after construction	■	■	·

D. Further reading

[Addleson 1989] p.76 Fig 15b, [Eldridge 1976] p. 102, [Eldridge 1976] p. 114, [Feilden 2003] Fig. 14.14e, [Hinks and Cook 1997] Fig. 10.9 b1, [Hinks and Cook 1997] Fig. 10.10, [Mastrodicasa 1993] Fig. 317, [Schubert 2009] case 2.4.2.

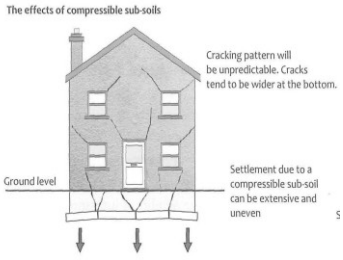
Damage pattern 51
Crack - in column or wall - combination of directions - no horizontal cracks - other combination of directions

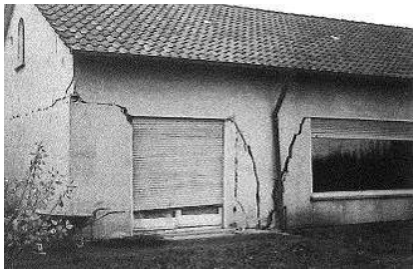
A. Damage pattern



symptoms:
- ■ S: crack
- ■ S: crack direction is not horizontal
- ■ S: other combination of crack directions

context conditions included in pattern:
- ■ G: damage appears in column or wall





Examples. [Eldridge 1976] p 136, [Marshall et al. 2009] p. 16, [Pfefferkorn 1994] Bild 216.

B. Hypotheses

- ☐ 1.A Vertical settlement: mid-settlement / both-ends-heave
- ☐ 1.B Vertical settlement: one-end-settlement / one-end-heave
- ☐ 1.C Vertical settlement: both-ends-settlement / mid-heave
- ☐ 2.3.1 Overloading due to change in resistance, geometrical discontinuities near opening

C. Essential conditions

For hypotheses and corresponding essential conditions of vertical settlement, see Part III of this tool.

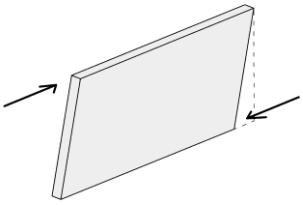
Additional symptom or context condition	**1.A**	**1.B**	**1.C**	**2.3.1**
G: damage appears near an opening	·	·	·	■

D. Further reading

[Eldridge 1976] p 136, [Marshall et al. 2009] p. 16, [Marshall et al. 2009] p.27, [Naldini et al. 2007], [Pfefferkorn 1994] Bild 216, [Schubert 2009] case 2.1.2.2,.

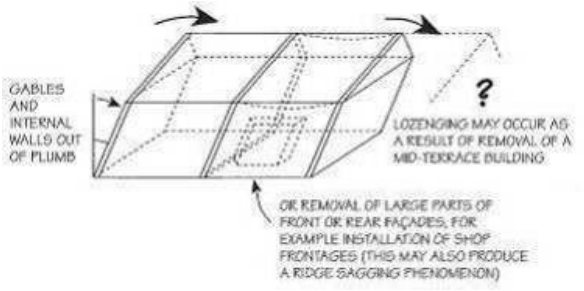
Damage pattern 52
Deformation - in column or wall - deformation in-plane - deviation from vertical

A. Damage pattern



symptoms:
- ■ S: deformation
- ■ S: deformation in-plane
- ■ S: deviation from vertical: vertical edge is not vertical anymore, out-of-plumb

context conditions included in pattern:
- ■ G: damage appears in column or wall



Examples. [Hinks and Cook 1997] Fig. 10.13, [Marshall et al. 2009] p. 29.

B. Hypotheses

- ☐ 2.2.2 Overloading due to change in load path, intervention, removal of mid-terrace building
- ☐ 2.2.3 Overloading due to change in load path, intervention, replacement of large part of façade
- ☐ 3.1.11 Hindered dimensional changes, temperature/moisture induced, lack of flexibility to accommodate movement

C. Essential conditions

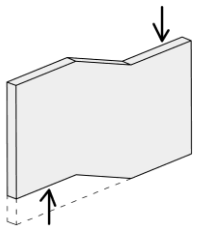
Additional symptom or context condition		2.2.2	2.2.3	3.1.11
G:	absence of sufficient expansion joints	·	·	■
G:	damage appears in flank wall of terrace	·	·	■
T:	damage has appeared after the following occurrence	■	■	·
G:	occurrence of replacement of large part of façade	·	■	·
E:	occurrence of removal of mid-terrace building	■	·	·

D. Further reading

[Hinks and Cook 1997] Fig. 10.13, [Marshall et al. 2009] p. 29.

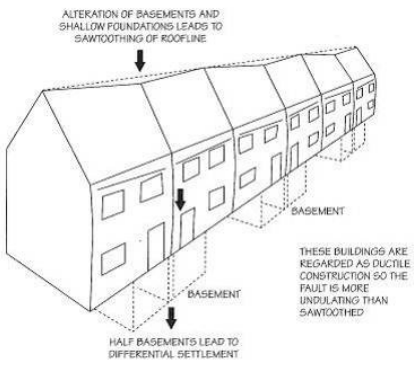
Damage pattern 53
Deformation - in column or wall - deformation in-plane - deviation from horizontal

A. Damage pattern



symptoms:
- ■ S: deformation
- ■ S: deformation in-plane
- ■ S: deviation from horizontal: bed joints are not horizontal anymore

context conditions included in pattern:
- ■ G: damage appears in column or wall



Examples. [Hinks and Cook 1997] Fig. 8.9, [Marshall et al. 2009] p. 14, [Warren 1999] Fig. 6.8.

B. Hypotheses

- ☐ 1.B Vertical settlement: one-end-settlement / one-end-heave
- ☐ 2.2.3 Overloading due to change in load path, intervention, replacement of large part of façade
- ☐ 2.3.1 Overloading due to change in resistance, geometrical discontinuities near opening

C. Essential conditions

For hypotheses and corresponding essential conditions of vertical settlement, see Part III of this tool.

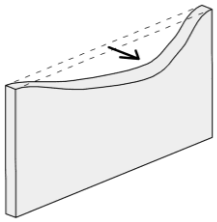
Additional symptom or context condition		1.B	2.2.3	2.3.1
G:	damage appears near an opening	·	·	■
T:	damage has appeared after the following occurrence	·	■	·
G:	occurrence of replacement of large part of façade	·	■	·

D. Further reading

[Cook and Hinks 1992] Fig. 6.1, [Harvey 2004] case 12, [Hinks and Cook 1997] Fig. 8.9, [Marshall et al. 2009] p. 14, [Marshall et al. 2009] p. 29, [Naldini et al. 2007], [Warren 1999] Fig. 6.8.

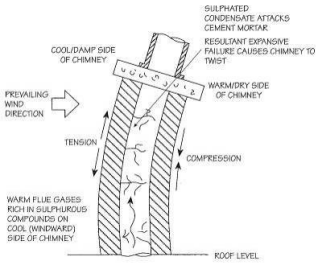
Damage pattern 54
Deformation - in column or wall - deformation out-of-plane - at top of building

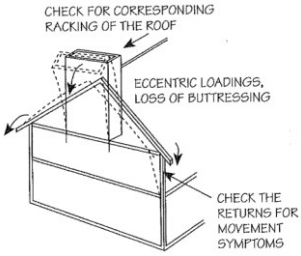
A. Damage pattern

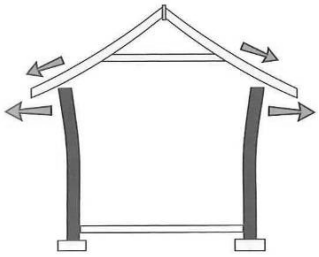


symptoms:
- ■ S: deformation
- ■ S: deformation out-of-plane
- ■ S: deformation out-of-plane, outward

context conditions included in pattern:
- ■ G: damage appears in column or wall
- ■ G: damage appears with maximum at top







Examples. [Hinks and Cook 1997] Fig. 2.8, [Hinks and Cook 1997] Fig. 10.24, [Marshall et al. 2009] p. 37f.

B. Hypotheses

- ☐ 2.1.4 Overloading due to change in load, horizontal, push of wind
- ☐ 2.1.5 Overloading due to change in load, horizontal, thrust of arch, vault or dome
- ☐ 2.1.7 Overloading due to change in load, horizontal, thrust of roof truss
- ☐ 2.1.9 Overloading due to change in load, horizontal, push of retained earth
- ☐ 2.2.1 Overloading due to change in load path, intervention, removal of lower portions of chimney
- ☐ 2.2.3 Overloading due to change in load path, intervention, replacement of large part of façade
- ☐ 2.3.1 Overloading due to change in resistance, geometrical discontinuities near opening
- ☐ 3.2 Hindered dimensional changes, due to frost action
- ☐ 3.4.2 Hindered dimensional changes, due to salt attack, formation of swelling compounds

C. Essential conditions

Additional symptom or context condition	2.1.4	2.1.5	2.1.7	2.1.9	2.2.1
G: damage appears in external building component	■	·	·	·	·
G: damage appears at or just below the springings	·	■	·	·	·
G: presence of arch, vault or dome adjacent to damaged area	·	■	·	·	·
G: damage appears at or just below roof level	·	·	■	·	·
G: damage appears in retaining wall	·	·	·	■	·
T: damage has appeared after the following occurrence	·	·	·	·	■
G: occurrence of removal of lower portions of chimney	·	·	·	·	■

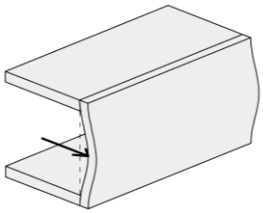
Additional symptom or context condition	2.2.3	2.3.1	3.2	3.4.2
M: damage appears in joints	·	·	·	■
S: crack	·	·	·	■
S: crack direction is horizontal	·	·	·	■
G: damage appears in external building component	·	·	■	■
G: damage appears near an opening	·	■	·	·
E: presence of source of moisture	·	·	■	■
G: damage appears with maximum halfway between two floors	·	·	■	·
E: presence of source of salt	·	·	·	■
T: damage has appeared after the following occurrence	■	·	·	·
G: occurrence of replacement of large part of façade	■	·	·	·
E: occurrence of temperatures below freezing point	·	·	■	·

D. Further reading

[Bakker 1963] Fig. 27, [Douglas and Ransom 2007] Fig. 14.2, [Eldridge 1976] p. 186, [Feilden 2003] Fig. 14.9, [Feilden 2003] Fig. 14.14c, [Harris 2001]p. 97, [Hinks and Cook 1997] Fig. 2.8, [Hinks and Cook 1997] Fig. 10.24, [Hinks and Cook 1997] Fig. 13.8, [Marshall et al. 2009] p. 37f [Marshall et al. 2009] p. 38 l, [Marshall et al. 2009] p. 47 e, f, [Marshall et al. 2009] p. 81 d, [Marshall et al. 2009] p. 82 a, [Marshall et al. 2009] p. 82 b, [Naldini et al. 2007], [Onsiteformasonry et al. 2002] par. 7.2.12 POLIMI, [Warren 1999] Fig. 8.6a, [Warren 1999] Fig. 8.6b.

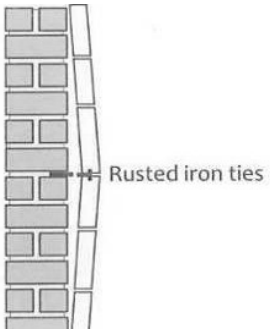
Damage pattern 55
Deformation - in column or wall - deformation out-of-plane - halfway the height - outward

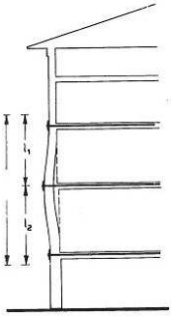
A. Damage pattern



symptoms:
- ■ S: deformation
- ■ S: deformation out-of-plane
- ■ S: deformation out-of-plane, outward

context conditions included in pattern:
- ■ G: damage appears in column or wall
- ■ G: damage appears with maximum halfway the height





Examples.[Marshall et al. 2009] p. 39 f, [Marshall et al. 2009] p. 38 g, [Mastrodicasa 1993] Fig. 127.

B. Hypotheses

- ☐ 2.1.4 Overloading due to change in load, horizontal, push of wind
- ☐ 2.1.5 Overloading due to change in load, horizontal, thrust of arch, vault or dome
- ☐ 2.1.7 Overloading due to change in load, horizontal, thrust of roof truss
- ☐ 2.1.9 Overloading due to change in load, horizontal, push of retained earth
- ☐ 2.2.4 Overloading due to change in load path, intervention, replacement of beam incorporated in wall
- ☐ 2.2.5 Overloading due to change in load path, bending, of floor supported by damaged wall
- ☐ 2.2.6 Overloading due to change in load path, bending, of floor that supports damaged wall
- ☐ 2.3.5 Overloading due to change in resistance, geometrical discontinuities in a cavity wall (wall tie deficiencies)
- ☐ 2.3.6 Overloading due to change in resistance, geometrical discontinuities within rubble-core masonry
- ☐ 3.1.2 Hindered dimensional changes, temperature/moisture induced, difference in behaviour between two types of mortar in masonry

☐ 3.1.3 Hindered dimensional changes, temperature/moisture induced, difference in behaviour between masonry and concrete
☐ 3.1.5 Hindered dimensional changes, temperature/moisture induced, difference in conditions between shady and sunny side
☐ 3.1.7 Hindered dimensional changes, temperature/moisture induced, difference in conditions between in-doors and out-of-doors
☐ 3.2 Hindered dimensional changes, due to frost action
☐ 3.3 Hindered dimensional changes, due to corrosion
☐ 3.4.2 Hindered dimensional changes, due to salt attack, formation of swelling compounds

C. Essential conditions

Additional symptom or context condition	2.1.4	2.1.5	2.1.7	2.1.9	2.2.4
G: damage appears in external building component	■	·	·	·	·
G: damage appears at or just below the springings	·	■	·	·	·
G: presence of arch, vault or dome adjacent to damaged area	·	■	·	·	·
G: damage appears at or just below roof level	·	·	■	·	·
G: damage appears in retaining wall	·	·	·	■	·
T: damage has appeared after the following occurrence	·	·	·	·	■
G: occurrence of replacement of beams incorporated in wall	·	·	·	·	■

Additional symptom or context condition	2.2.5	2.2.6	2.3.5	2.3.6	3.1.2
M: damage appears along the horizontal edges of units	·	·	·	■	·
M: presence of joints that have been repointed	·	·	·	·	■
G: damage appears in external building component	·	·	·	·	■
G: damage appears in wall that supports the floor	■	·	·	·	·
G: damage appears with maximum at or near floor level	■	·	·	·	·
G: damage appears in wall that is supported by floor	·	■	·	·	·
G: damage appears in cavity wall	·	·	■	·	·
G: damage appears in rubble core masonry that has thin shell and high load	·	·	·	■	·

Additional symptom or context condition	3.1.3	3.1.5	3.1.7	3.2	3.3
S: rust stains	·	·	·	·	■
M: presence of a concrete frame, with masonry used as infill	⑤	·	·	·	·
M: presence of a concrete floor slab	①	·	·	·	·
M: damage appears at location of iron element	·	·	·	·	■
M: presence of iron element embedded in masonry	·	·	·	·	■
G: damage appears in external building component	·	·	·	■	·
G: damage appears with maximum at or near floor level	①	·	·	·	·
E: presence of source of moisture	·	·	·	■	·
G: damage appears with maximum halfway between two floors	·	·	·	■	·
G: absence of sufficient expansion joints	·	■	■	·	·
G: damage appears at corner	·	■	·	·	·
G: damage appears at connection between internal and external wall	·	·	■	·	·
E: occurrence of temperatures below freezing point	·	·	·	■	·

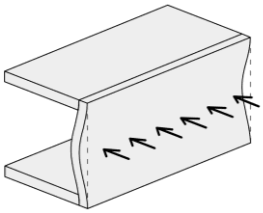
Additional symptom or context condition	3.4.2
M: damage appears in joints	■
S: crack	■
S: crack direction is horizontal	■
G: damage appears in external building component	■
E: presence of source of moisture	■
E: presence of source of salt	■

D. Further reading

[Addleson 1989] Fig. 9, [Addleson 1989] p.93 Fig 5, [Beckmann and Bowles 2004] fig. 4.11 a+b, [Eldridge 1976] p. 144, [Feilden 2003] Fig. 14.15b, [Feilden 2003] Fig. 14.15c, [Harris 2001] p. 98, [Harvey 2004] case 1, [Harvey 2004] case 29, [Hinks and Cook 1997] Fig. 9.37, [Hinks and Cook 1997] Fig. 10.4, [Hinks and Cook 1997] Fig. 10.5, [Hinks and Cook 1997] Fig. 10.20, [Marshall et al. 2009] p. 38 e, f, [Marshall et al. 2009] p. 38 g, [Marshall et al. 2009] p. 39 f, [Marshall et al. 2009] p. 40 b, c, [Marshall et al. 2009] p. 47 b, [Marshall et al. 2009] p. 47 d, g, h, [Marshall et al. 2009] p. 221 c, [Mastrodicasa 1993] Fig. 121 + 122, [Mastrodicasa 1993] Fig. 127, [Mastrodicasa 1993] Fig. 136, [Mastrodicasa 1993] Fig. 142, [Naldini et al. 2007], [Onsiteformasonry et al. 2002] par. 7.2.12 POLIMI, [Pieper 1983] Bild 18.18 (detail), [Warren 1999] Fig. 6.6, [Total Wall Concept 2006].

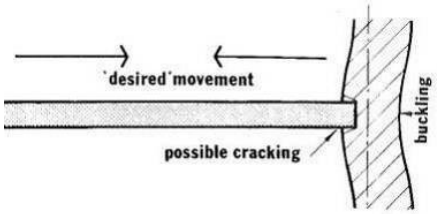
Damage pattern 56
Deformation - in column or wall - deformation out-of-plane - halfway the height - inward

A. Damage pattern



symptoms:
- ■ S: deformation
- ■ S: deformation out-of-plane
- ■ S: deformation out-of-plane, inward

context conditions included in pattern:
- ■ G: damage appears in column or wall
- ■ G: damage appears with maximum halfway the height



Examples. [Addleson 1989] Fig. 24.9.

B. Hypotheses

☐ 3.1.3 Hindered dimensional changes, temperature/moisture induced, difference in behaviour between masonry and concrete

C. Essential conditions

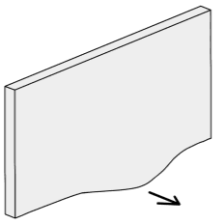
Additional symptom or context condition	**3.1.3**
M: presence of a concrete floor slab	■
G: damage appears with maximum at or near floor level	■

D. Further reading

[Addleson 1989] Fig. 24.9.

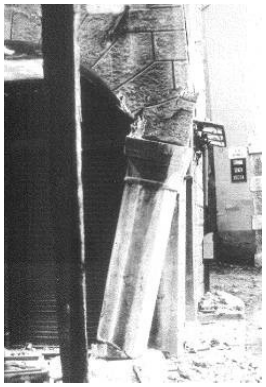
Damage pattern 57
Deformation - in column or wall - deformation out-of-plane - at bottom of building

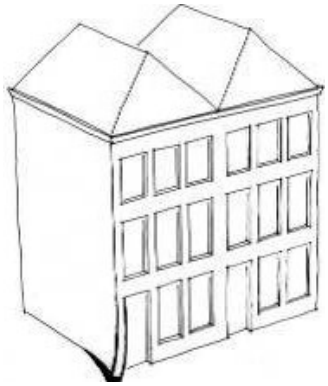
A. Damage pattern



symptoms:
- ■ S: deformation
- ■ S: deformation out-of-plane
- ■ S: deformation out-of-plane, outward

context conditions included in pattern:
- ■ G: damage appears in column or wall
- ■ G: damage appears with maximum in base





Examples. [Croci 1998] Fig. 6.28, [Naldini et al. 2007].

B. Hypotheses

- ☐ 1.B Vertical settlement: one-end-settlement / one-end-heave
- ☐ 2.1.10 Overloading due to change in load, horizontal, push of tree roots
- ☐ 2.1.15 Overloading due to change in load, vibrational, natural or induced earthquake
- ☐ 2.1.16 Overloading due to change in load, vibrational, machinery or traffic

C. Essential conditions

For hypotheses and corresponding essential conditions of vertical settlement, see Part III of this tool.

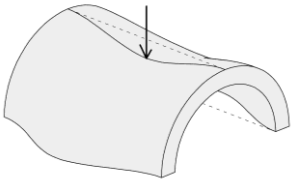
	Additional symptom or context condition	1.B	2.1.10	2.1.15	2.1.16
G:	damage appears in free-standing wall	·	■	·	·
E:	presence of tree adjacent to building, at side of damage	·	■	·	·
T:	damage has appeared after the following occurrence	·	·	■	■
E:	occurrence of seismic event	·	·	■	·
E:	occurrence of vibrations with considerable amplitude, due to machinery or traffic	·	·	·	■

D. Further reading

[Croci 1998] Fig. 6.28, [Naldini et al. 2007].

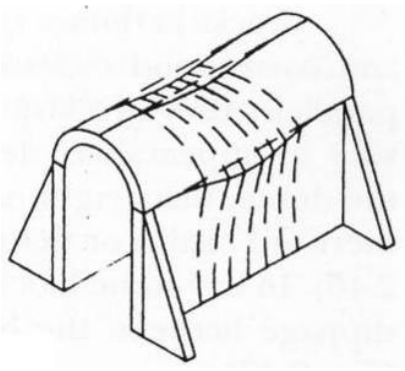
Damage pattern 58
Deformation - in arch, vault or dome - symmetrical

A. Damage pattern



symptoms:
- ■ S: deformation
- ■ S: deformation out-of-plane
- ■ S: damage is symmetric with respect to a vertical plane along the crown
- ■ S: curve of arch is flattened halfway span (arch sag)

context conditions included in pattern:
- ■ G: damage appears in arch, vault or dome



Examples. [Croci 1998] Fig. 2.43, [Croci 1998] Fig. 2.44 b.

B. Hypotheses

- ☐ 2.1.1 Overloading due to change in load, vertical, increase in self-weight, at time of construction
- ☐ 2.1.2 Overloading due to change in load, vertical, increase in self-weight, extensions built in or onto building
- ☐ 2.3.9 Overloading due to change in resistance, decrease in capacity of masonry, due to creep

C. Essential conditions

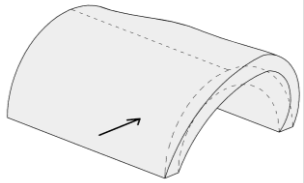
	Additional symptom or context condition	2.1.1	2.1.2	2.3.9
M:	presence of lime-based mortar	·	·	■
G:	presence of high (gravity) load	·	·	■
T:	damage has appeared after the following occurrence	·	■	·
G:	occurrence of extension built in or on top of existing building	·	■	·
T:	damage has appeared gradually, over a considerable period of time	·	·	■
T:	damage has appeared in the first years after construction	■	·	·

D. Further reading

[Croci 1998] Fig. 2.43, [Croci 1998] Fig. 2.44 b.

Damage pattern 59
Deformation - in arch, vault or dome - asymmetrical

A. Damage pattern



symptoms:
- ■ S: deformation
- ■ S: deformation in-plane
- ■ S: damage is asymmetric with respect to a vertical plane along the crown
- ■ S: curve of arch is sharpened to one side, flattened to other side (arch sway)

context conditions included in pattern:
- ■ G: damage appears in arch, vault or dome

Examples. [Harvey 2004] case 3, [Harvey 2004] case 4.

B. Hypotheses

- ☐ 1.B Vertical settlement: one-end-settlement / one-end-heave
- ☐ 2.1.1 Overloading due to change in load, vertical, increase in self-weight, at time of construction
- ☐ 2.1.2 Overloading due to change in load, vertical, increase in self-weight, extensions built in or onto building
- ☐ 2.1.3 Overloading due to change in load, vertical, increase in use load
- ☐ 2.2.9 Overloading due to change in load path, horizontal displacement of supports

C. Essential conditions

For hypotheses and corresponding essential conditions of vertical settlement, see Part III of this tool.

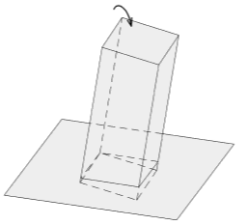
Additional symptom or context condition	1.B	2.1.1	2.1.2	2.1.3	2.2.9
G: damage appears in support of arch, vault or dome	·	·	·	·	■
S: deviation from vertical: vertical edge is not vertical anymore, out of plumb	·	·	·	·	■
T: damage has appeared after the following occurrence	·	·	■	■	·
G: occurrence of extension built in or on top of existing building	·	·	■	·	·
E: occurrence of change in use	·	·	·	■	·
T: damage has appeared in the first years after construction	·	■	·	·	·

D. Further reading

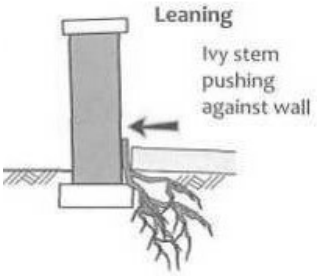
[Harvey 2004] case 3, [Harvey 2004] case 4.

Damage pattern 60
Tilt

A. Damage pattern



symptoms:
■ S: tilt



Examples. [Marshall et al. 2009] p. 47 f, [Meichsner and Rohr-Suchalla 2008] Bild 172, [Warren 1999] Fig. 5.8.

B. Hypotheses

☐ 1.B Vertical settlement: one-end-settlement / one-end-heave
☐ 2.1.10 Overloading due to change in load, horizontal, push of tree roots

C. Essential conditions

For hypotheses and corresponding essential conditions of vertical settlement, see Part III of this tool.

Additional symptom or context condition	**1.B**	**2.1.10**
G: damage appears in free-standing wall	·	■
E: presence of tree adjacent to building, at side of damage	·	■

NB Tilt can also be intended, as part of the original design “Es gibt aber auch gewollte und daher zu erhaltende Schiefstellungen an historischen Mauerwerken, etwa an Stützmauern oder an Kirchenwänden.“ [Maier 2002] p. 122

D. Further reading

[Hinks and Cook 1997] Fig. 15.1, [Kastner et al. 2003] Fig. 4.2, [Kastner et al. 2003] Fig. 5.3b, [Kastner et al. 2003] Fig. 5.6, [Kastner et al. 2003] Fig. 5.7, [Kastner et al. 2003] Fig. 5.8, [Marshall et al. 2009] p. 7, [Marshall et al. 2009] p. 15, [Marshall et al. 2009] p. 47 f, [Meichsner and Rohr-Suchalla 2008] Bild 172, [Naldini et al. 2007], [Pfefferkorn 1994] Bild 221, [Stichting Bouwresearch 1975] Foto 43, [Warren 1999] Fig. 5.8.

Part III

Hypotheses and essential conditions for settlement

Vertical settlement

B. Hypotheses

- ☐ 1.1.1 Differential settlement due to change in load, differences in self-weight of the building
- ☐ 1.1.2 Differential settlement due to change in load, differences in use load
- ☐ 1.1.3 Differential settlement due to change in load, uneven distribution of loads on the foundations
- ☐ 1.2.1 Differential settlement due to change in foundation behaviour, differences in foundation type or depth
- ☐ 1.2.2 Differential settlement due to change in foundation behaviour, differences in basement layout
- ☐ 1.2.3 Differential settlement due to change in foundation behaviour, local decline due to wood rot
- ☐ 1.2.4 Differential heave due to change in foundation behaviour, salt attack on the foundations
- ☐ 1.3.1 Differential settlement due to change in soil behaviour, differences in soil composition
- ☐ 1.3.2 Differential settlement due to change in soil behaviour, differences in effective stress due to removal of soil
- ☐ 1.3.3 Differential settlement due to change in soil behaviour, differences in pore (water) pressure
- ☐ 1.3.4 Differential settlement due to change in soil behaviour, differences in load imposed on the soil (not from damaged building itself)
- ☐ 1.3.5 Differential heave due to change in soil behaviour, differences in pore (water) pressure
- ☐ 1.3.6 Differential heave due to change in soil behaviour, local uplift by tree roots
- ☐ 1.3.7 Differential soil movement due to change in soil behaviour, vibrations in the soil

C. Essential conditions

Essential symptoms and context conditions	1.1.1	1.1.2	1.1.3	1.2.1	1.2.2
G: presence of difference in loading between damaged and adjacent part of the building	■	·	·	·	·
G: presence of difference in loading between damaged and adjacent part of the building	·	■	·	·	·
G: presence of eccentric load on foundations	·	·	■	·	·
G: presence of difference in foundations below damaged and adjacent part of the building	·	·	·	■	·
G: presence of basement that extends only below part of the damaged building	·	·	·	·	■

Essential symptoms and context conditions	1.2.3	1.2.4	1.3.1	1.3.2	1.3.3
M: presence of timber (pile) foundation	■	·	·	·	·
M: presence of cement-based mortar in foundations	·	①	·	·	·
M: presence of hydraulic lime mortar in foundations	·	②	·	·	·
E: presence of source of moisture	·	■	·	·	·
E: presence of source of salt	·	■	·	·	·
E: presence of difference in soil conditions below the damaged building	·	·	①	·	·
E: presence of geological fault line	·	·	②	·	·
E: presence of clay ground					①-②
E: presence of tree adjacent to building, at side of damage	·	·	·	·	②
T: damage has appeared after the following occurrence:	·	·	·	①-⑥	①-②
E: occurrence of deep excavation adjacent to the building	·	·	·	①	·
E: occurrence of tunnelling	·	·	·	②	·
E: occurrence of landslide	·	·	·	③	·
E: occurrence of mining	·	·	·	④	·
E: occurrence of leakage	·	·	·	⑤	·
E: occurrence of flood	·	·	·	⑥	·
E: occurrence of extremely dry weather	·	·	·	·	①-②

Essential symptoms and context conditions	1.3.4	1.3.5	1.3.6	1.3.7
G: presence of shallow foundation that does not extent below frost depth (ca 600 mm deep)	·	④	·	·
E: presence of compressible soil	■	·	·	·
E: presence of clay ground	·	①-③	·	·
E: presence of silt, fine sand, or chalk soil	·	④	·	·
E: presence of source of moisture	·	④	·	·
E: presence of tree adjacent to building, at side of damage	·	·	■	·
T: damage has appeared after the following occurrence:	■	①-④	·	■
E: occurrence of construction of a new building adjacent to the damaged building	■	·	·	·
E: occurrence of leakage	·	①	·	·
E: occurrence of wet weather after extremely dry weather	·	②	·	·
E: occurrence of removal of tree adjacent to building, at side of damage	·	③	·	·
E: occurrence of high ground water table	·	④	·	·
E: occurrence of temperatures below freezing point	·	④	·	·
E: occurrence of seismic event	·	·	·	■

Horizontal settlement

B. Hypotheses

☐ 1.3.2 Differential settlement due to change in soil behaviour, differences in effective stress due to removal of soil

☐ 1.3.7 Differential soil movement due to change in soil behaviour, vibrations in the soil

C. Essential conditions

Essential symptoms and context conditions		**1.3.2**	**1.3.7**
T:	damage has appeared after the following occurrence:	①-⑥	■
E:	occurrence of deep excavation adjacent to the building	①	·
E:	occurrence of tunnelling	②	·
E:	occurrence of landslide	③	·
E:	occurrence of mining	④	·
E:	occurrence of leakage	⑤	·
E:	occurrence of flood	⑥	·
E:	occurrence of seismic event	·	■

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This prototype of a diagnostic decision support tool for structural damage in traditional masonry is the result of a PhD research project. The research project has aimed to improve and facilitate the diagnostic process by offering support in the initial phase in which hypotheses are generated. The more precise hypotheses are formulated, and the more accurate they are classified, the more effective the further process of verification will be and the greater the probability that the final diagnosis is correct.

Based on an extensive literature review of over 500 cases of structural damage, 60 characteristic damage patterns have been identified. For each of these damage patterns, possible causes have been listed. Essential context conditions (in terms of material, geometry, environment and time) allow one to discriminate between these hypotheses. A decision tree helps users determine which of the 60 damage patterns most closely matches the damage they are investigating. All further information on hypotheses and conditions is provided tailored to the selected pattern. For settlement-related damage processes, a separate part gives more details on underlying causes and essential conditions.

For more background information on the development of this tool and on the terms used in it, the reader is referred to the PhD thesis ‘Structural damage in masonry: Developing diagnostic decision support’ (ISBN: 978-90-8570-759-2).

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