

Building Damage due to Explosions in Urban Environment

Part 2

Manual and Practical Application of the Blast Damage Assessment Tool

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ABSTRACT

The presented manual covers building damage due to air blasts in urban environment. It is based on the previously presented rule-of-thumb model [1]. The objective of the manual is to provide a practical tool to enable quick assessments of building damages caused by explosions. The manual is not provided as building design guideline for structural engineers. It rather addresses a widespread audience like emergency measures personnel, governmental organizations conducting risk assessments or planners arranging security measures e.g. perimeter protection devices. The manual will be published on behalf of the Board of Experts for Military Infrastructure Protection, Swiss Federal Department of Defence, Civil Protection and Sport.

STARTING SITUATION, OBJECTIVE AND SCOPE

Building damage assessment is a quite difficult process because experience in the topics of explosion mechanics and effects as well as in structural dynamics is needed. Furthermore, numerical simulations of blast effects and the structural behavior of buildings can be very time consuming and the required sophisticated tools are not practicable for the mentioned user. The presented, on practice-focused manual was developed with the intention to find an appropriate balance between physically correct predictions of blast effects and the feasibility of such information in the practical use. Experience is indicating that practical fundamentals, such as the FEMA Risk Management Series [2] are of great interest.

Regarding the scope the blast damage assessment tool covers hazards due to explosions of improvised explosive devices (IED) with charge weights from 10 to 10'000 kg TNT. For urban environment with typical Swiss or European design and structures the manual provides a simple, fast usable and pragmatic application tool for assessing and estimating potential building damage.

The effects of explosions are spreads of air blasts, fragments throw and also thermal effects from the fireball. All these effects can cause damage to persons and buildings. Debris of damaged buildings e.g. debris of fractured glazing is mainly responsible for fatalities and injuries to persons (Figure 1).

The presented tool deals with building damage due to blast effects. The Swiss *Board of Experts for Military Infrastructure Protection* who launched this manual, is planning further research and development of a second part of this manual, which will focus on damage to persons.

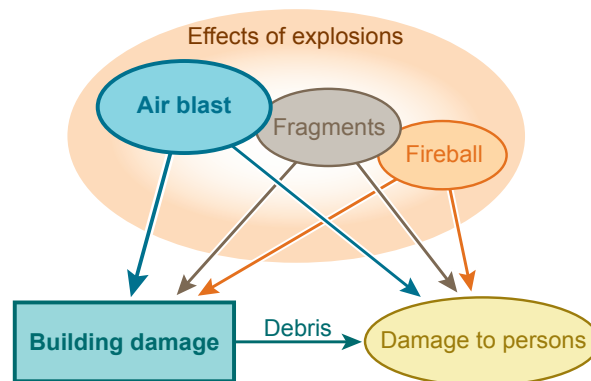


Figure 1. Effects of explosions

AIR BLAST AND BLAST LOADING

Hemispherical blast propagation

The detonation of explosives is a fast chemical reaction. Due to the energy release the explosion produces a transient air pressure wave called air blast. For a ground-level explosion, such as an explosion of an IED, the blast will propagate from the burst in the form of a hemispherical wave front [3]. The blast wave is characterized by a steep shock front, the peak overpressure p and the impulse i . The impulse is according to the blast energy and illustrated as the area under the overpressure time history. The peak overpressure decreases rapid (to the power of 3) with increasing range R . The decrease of the impulse is less distinctive. There is a physically given correlation of the four parameters, the charge W , the range R , the peak overpressure p and the impulse i . Figure 2 shows this correlation. Blast parameters in this chart were calculated with the program *ConWep* according to the Technical Manual TM-855-1 [4].

P-I diagram

The *P-I* diagram is a useful design tool that permits easy assessment of response to a specific blast load. The diagram, as shown in Figure 2, indicates the combinations of load or peak overpressure and impulse that will cause failure or a specific damage [5]. Combinations of pressure and impulse that fall to the right and above the iso-damage curve will cause damage.

An impulsive loading implies that the blast duration is short in relation to the response time of the building structure. The load applies to the structure and removes before the structure responds and undergoes any significant deformation. In this case the maximum response of the structure is not affected by the loading history and damage in the impulsive loading region is therefore also not dependent on the peak overpressure of the blast. If on the opposite the blast duration is significantly longer than the response time of the structure hit, the loading is quasi-static. In this loading regime the load dissipates very little before the structure responds e.g. the maximum deformation or resistance is achieved. Then, the respond of the structure depends only upon the peak overpressure. Dynamic loadings between these two loading regimes are more complex, because the structural response is influenced by the profile of the load history.

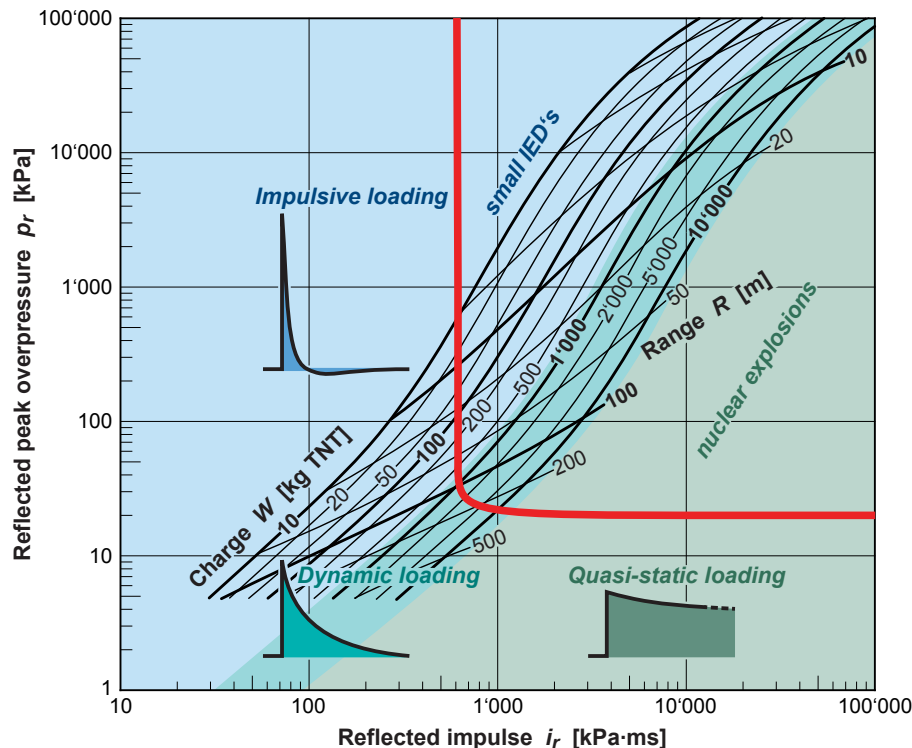


Figure 2. *P-I* diagram with iso-damage curve and different loading regimes

Blast loading due to improvised explosive devices

Figure 2 shows a P - I diagram with a typical iso-damage curve for building damage due to blast. Observing the charge W in the diagram, one can recognize that for explosives with a few hundred kilograms of TNT impulsive loading is decisive. Considering the hazard due to IEDs, as it will be explicated later on, most IEDs have charge weights in this order. Quasi-static loading which uses only the peak overpressure as damage criterion is decisive in case of very large charges over 10'000 kg TNT. However, VBIEDs with such large charges are quite improbable. Thus, quasi-static loading is mainly important for protection devices, like shelters, which are designed against threats due to massive destruction devices e.g. nuclear weapons.

W - R diagram

The blast parameters pressure and impulse are basics for the design. However, conducting a blast damage assessment for built structures, the direct relation of the mass of explosive W and the range R is of prior interest. Therefore, the presented manual handles with W - R diagrams, which are more appropriate for the practical use. Figure 3 shows exemplified the identical iso-damage curve like the P - I diagram, Figure 2.

Many older basics which indicates building damage due to blast effects, e.g. the manual LS 2009-05 [6] or the table used by ATF [7] to determine the recommended evacuation distance, uses only the peak overpressure as damage criterion. The reason for that are descriptions of blast damage, which often are based on research due to the effects of nuclear weapons. In Figure 3, for example, the damage line for failure of masonry walls is plotted. This line corresponds with a reflected peak overpressure of $p_r = 20$ kPa. However, for the explosion of IEDs with relative small charges, the impulsive loading regime is decisive. The use of peak overpressure as damage criterion is needless conservative then. This fact is exemplarily represented by a comparison of the two iso-damage lines in Figure 3.

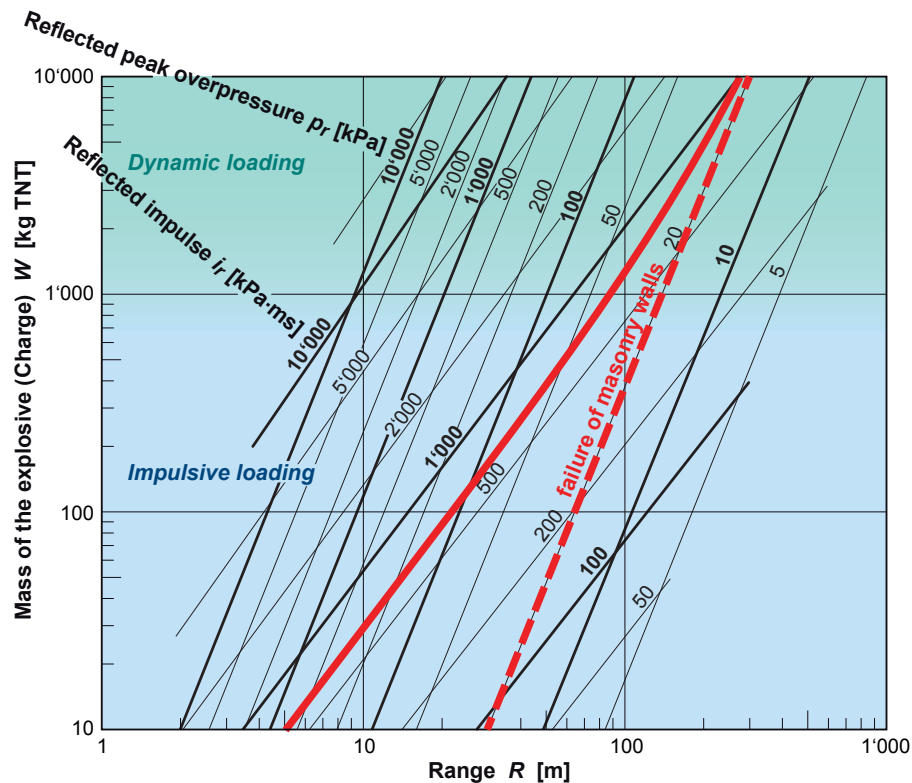


Figure 3. W - R diagram with identical iso-damage curve, plotted in Figure 2. The dotted line represents an example of a damage threshold due to older basics, which is only based on the peak overpressure criterion.

HAZARD ANALYSIS AND BUILDING DAMAGE ASSESSMENT

Approach

The practical approach for the hazard analysis and the building damage assessment implies the following steps illustrated in Figure 4. In a first step, a realistic estimation of the hazard is needed. After that, the buildings in the vicinity of the potential explosion have to be judged regarding their construction. As a basis for the pragmatic assessment, furthermore a suitable definition of building damage grades is needed. At least, the ranges R for the defined building damage grades will be determined. The presented easy to handle approach gives a realistic idea of expected damage patterns.

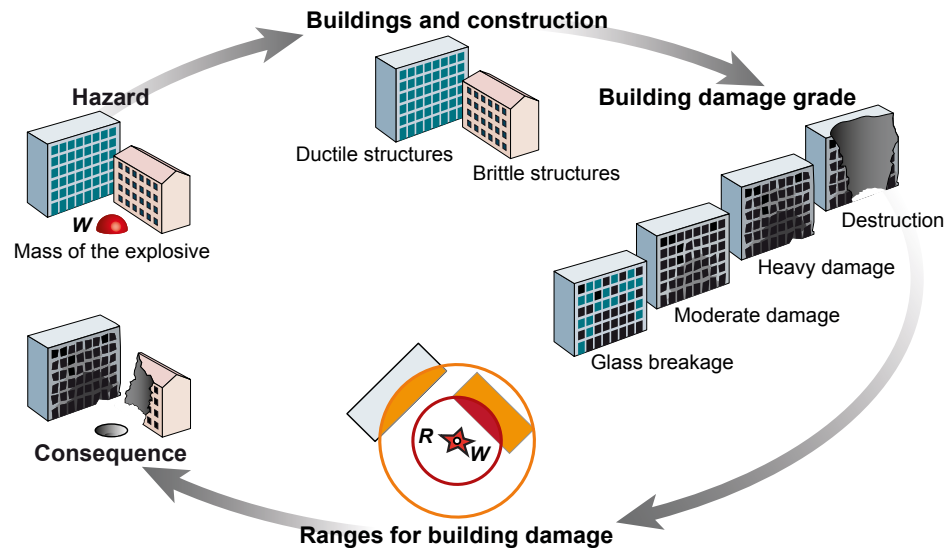


Figure 4. Approach for the hazard analysis and the building damage assessment

Hazard

Table 1 shows a comparison of the definition for hazard due to VBIED from different sources. STANAG 2280 [6] describes the design threat level for temporary protective structures. The Swiss manual LS 2009-05 [7] uses a quite similar hazard definition. The assessment for typical threats from the American Society of Concrete Engineers (ASCE) [8] differs a little, mainly considering the large explosive weights respectively the high hazards. Nevertheless, this definition has to be estimated as the most realistic one. The postulated hazard definition, used in the presented manual, is made up of four hazard levels and is also shown in Table 1.

	STANAG 2280	LS 2009-05	ASCE	Hazard
10				
	1		Low (Car)	low
	Motorbike			
50			Medium (Car)	
				50 kg TNT
100	2	Lightweight passenger car		moderate
	Passenger vehicle			
			High (Truck)	
				250 kg TNT
500	3	Large passenger car		high
	Van			
1'000		Van, light truck	Very high (Truck)	
				1000 kg TNT
	4			
	Medium truck			
5'000	5	Truck		very high
	Heavy truck			
10'000				

Table 1. Comparison of hazard due to VBIED according to STANAG 2280 [8], Manual LS 2009-05 [6] and ASCE [9] as well as the postulated hazard definition

Buildings and construction

To execute the building damage assessment, some basic information about the different building construction types is needed. Concerning the aspects of structural engineering, building structures can be classified into solid constructions and frame or skeleton constructions.

Solid structures are usually built with masonry. Mainly older and even historical buildings are of this type, but also structures of newer buildings are built with masonry bearing walls. Solid constructions with reinforced concrete structures are rather seldom. However, it has to be mentioned that solid and frame constructions often are combined and also in frame constructions parts of the structure, e.g. shear walls, have a solid structure design.

Modern buildings and mainly large office buildings are built as frame or skeleton constructions in almost all cases. In Switzerland such structures are mainly built as in-situ or as prefabricated reinforced concrete frames. With exception of industrial buildings, steel structures are less common because of the required fire protection measures.

As already indicated in [1] it is sufficiently accurate to distinguish the construction types in ductile and less ductile or brittle structures. In doing so, masonry buildings have to be classified as brittle. Reinforced concrete as well as steel structures will be regarded as ductile.

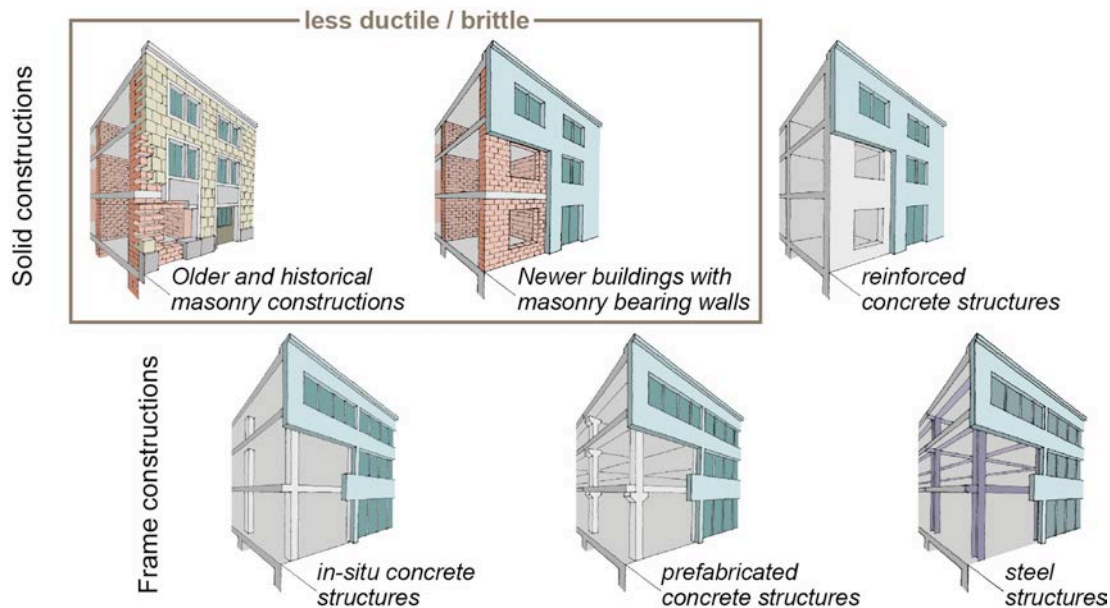


Figure 5. Summary of building construction types

Building damage grade

Different levels for building damage have been defined in various basics e.g. in documents of the U.S. Army corps of engineers [10]. Also in the presentation before, a comprehensive summary of the definitions of various damage models was given [1].

Within the scope of the desired pragmatic approach, the presented manual handles only four damage grades. This approach is easy to apply and appropriately accurate. The following Table 2 shows an abstract of the building damage levels used in the manual. These damage grades concern the building structure, respectively the structural elements, the building envelope, like facades or cladding as well as windows and glazing. Additionally, also damage on non-structural elements like partition walls, suspended ceilings, infrastructure or even furnishing were described.

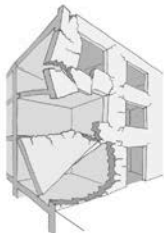
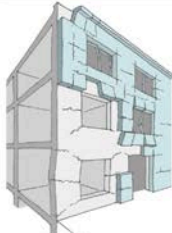


Destruction		<ul style="list-style-type: none"> ■ The structural elements show very serious damage and have partially or completely failed. ■ The building envelope is totally destroyed or completely blown-out. □ Also those buildings which have not collapsed are hazardous. Repair is hardly possible and the building has to be pulled down.
Heavy damage		<ul style="list-style-type: none"> ■ The structure shows partially significant damage, but it will not collapse. ■ Especially on the side exposed to the explosion, the building envelope is badly damaged. □ In numerous cases the building has to be pulled down, because restoring would be extensive and not cost-effective.
Moderate damage		<ul style="list-style-type: none"> ■ The structural safety is not at risk due to damage on the structural elements. ■ Damage on the building envelope, primarily on the facade exposed to the explosion. □ The building can not be used temporarily and must be inspected, repaired and restored.
Glass breakage		<ul style="list-style-type: none"> ■ The structural elements do not show any damage. The structural safety is given. ■ No or only marginal damage on the facades, partly broken glass, especially at the glazing exposed to the explosion. □ Rooms with broken glass can only be used limited until repairs. A safety control of the structure is generally not required.

Table 2. Building damage grades

Range for building damage

Corresponding with the hemispherical air blast propagation, the ranges for certain building damage have a hemispherical shape too. Figure 6 illustrates the ranges for destruction R_d , for heavy damage R_h and for moderate damage R_m . With the exception of very high hazards the range for building destruction R_d is in the order of just a few meters. Therefore, the hemispherical shape of the destruction range must be taken into account. The model contains appropriate guidance for the assessment of local destruction or the occurrence of progressive collapses for such cases. For moderate damage or even glass breakage the damage ranges are usually more than hundred meters. Building damage is hardly affected by the hemispherical range then.

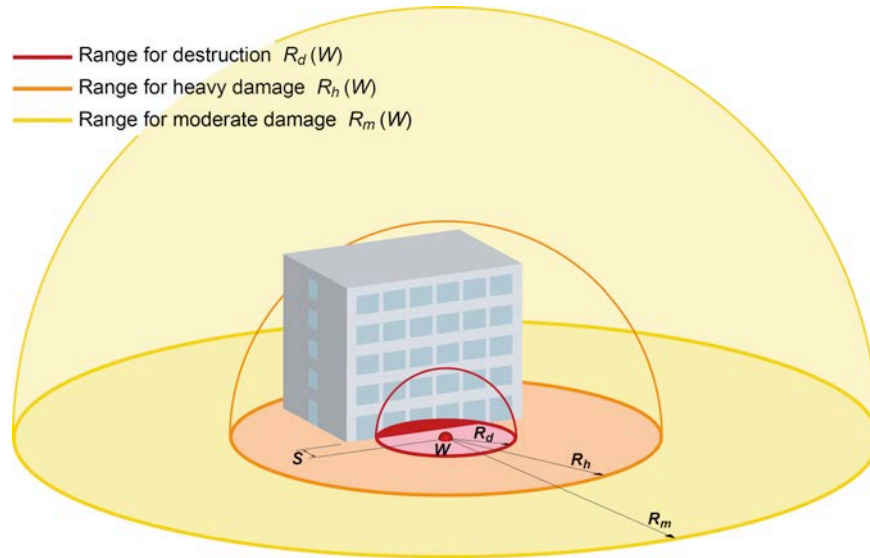


Figure 6. Ranges for building damage

As a function of the mass of explosive W , the ranges R for destruction, heavy damage and moderate damage are plotted in a W - R diagram, shown in Figure 7. It should be noted that for moderate damage a differentiation between ductile and brittle structures is not necessary because such damage mainly concern damage to the building facades. In addition the manual also gives information about the likelihood of glass breakage. The shape and the steepness of this damage thresholds indicate that in this case the peak overpressure of the blast is much more decisive than the impulse (compare also Figure 3).

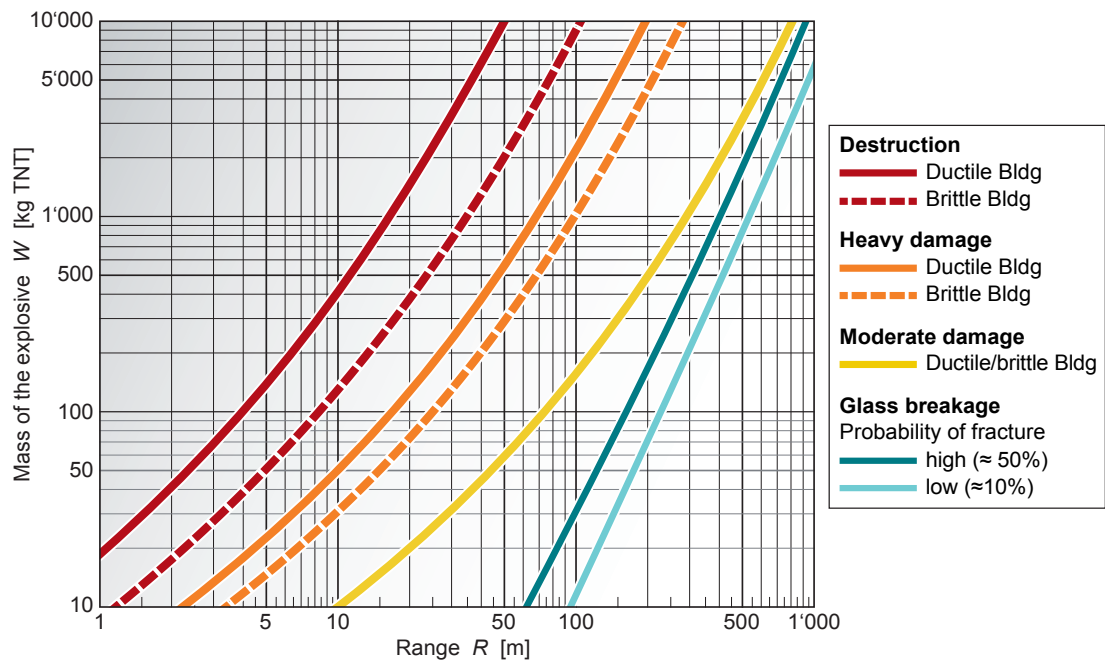


Figure 7. W - R diagram for different damage grades and different building construction types

PRACTICAL TOOL AND EXAMPLE OF USE

The presented manual provides a clear, easy to handle and useful working tool for a widespread audience like emergency measures personnel, governmental organizations conducting risk assessments or planners arranging security measures e.g. perimeter protection devices. By following a few simple steps it is possible to gain a realistic overview of the damage patterns due to explosions in urban environment. Hereafter an example of the practical application of a damage assessment for the downtown area of a Swiss city is illustrated.

Step 1: Hazard

In the first step a judgment of the expected hazard is required. For a possible terrorist threat with a VBIED in a passenger car a hazard level of moderate to high can be estimated. With the help of the following Figure 8 a mass of explosive of 250 kg TNT is assumed.

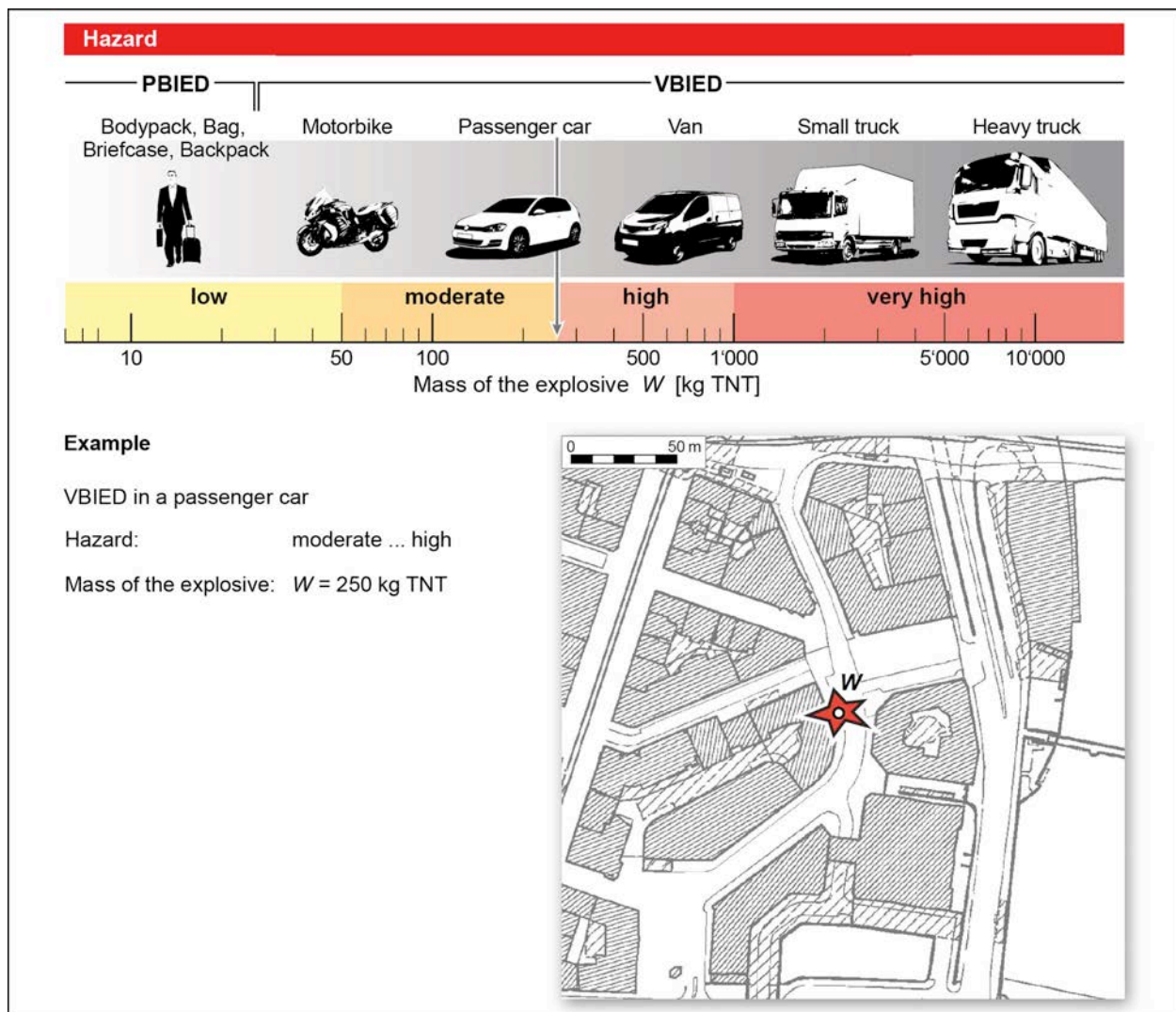


Figure 8. Practical tool and example of use: Hazard

Step 2: Buildings and construction

To carry on with the second step a judgment of the building construction in the area close to the center of the explosion is necessary. Of course it is impossible to conduct an in-depth analysis of the structural design of the affected buildings. However, for an easy distinction in ductile and brittle constructions this is usually not necessary either. The manual delivers illustrative explanation for a quick visual assessment of constructions (Figure 9).

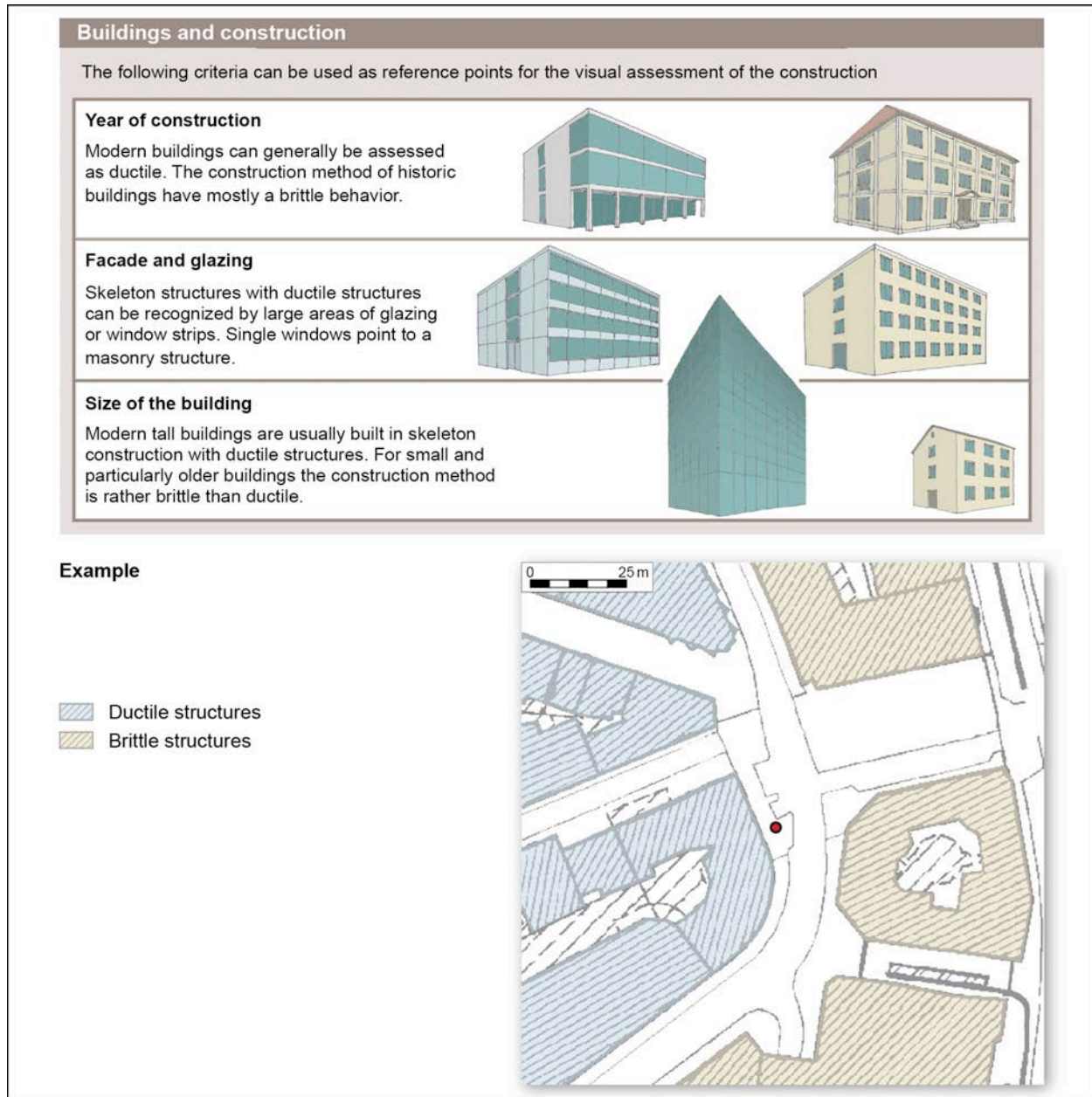


Figure 9. Practical tool and example of use: Buildings and construction

Step 3: Ranges for building damage

By proceeding with step 3 the estimation of the range for building destruction, heavy damage and moderate damage is being done. In order to give a clear overview, the application tool provides a comprehensive description of the building damage for every damage grade. The following figures are showing these summaries as well as the *W-R* diagrams and the map detail with the plotted in damage ranges for the example.

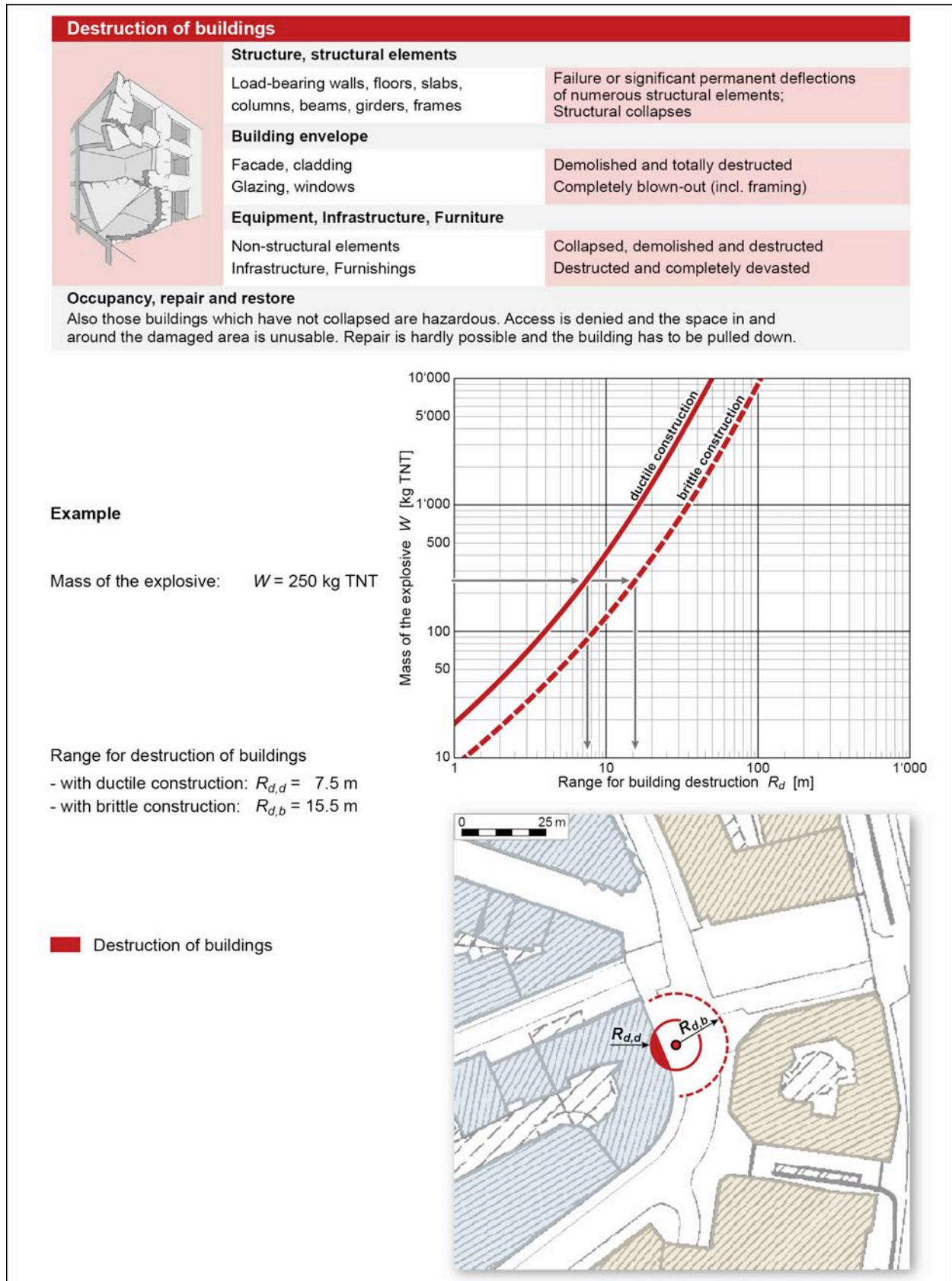


Figure 10. Practical tool and example of use: Destruction of Buildings

Within the destruction range an improved assessment of the expected building damage is necessary. Depending on the destructed buildings area and also the building sizes, the destruction is only situated locally, or, due to progressive collapse, larger building areas are involved. The chart, Figure 11, provides an indication of such estimations. For the example with a 250 kg TNT charge which explodes in a stand-off distance $S = 5$ m, only local destruction has to be expected. It may be assumed that in case of a large building, a progressive collapse is quite improbable.

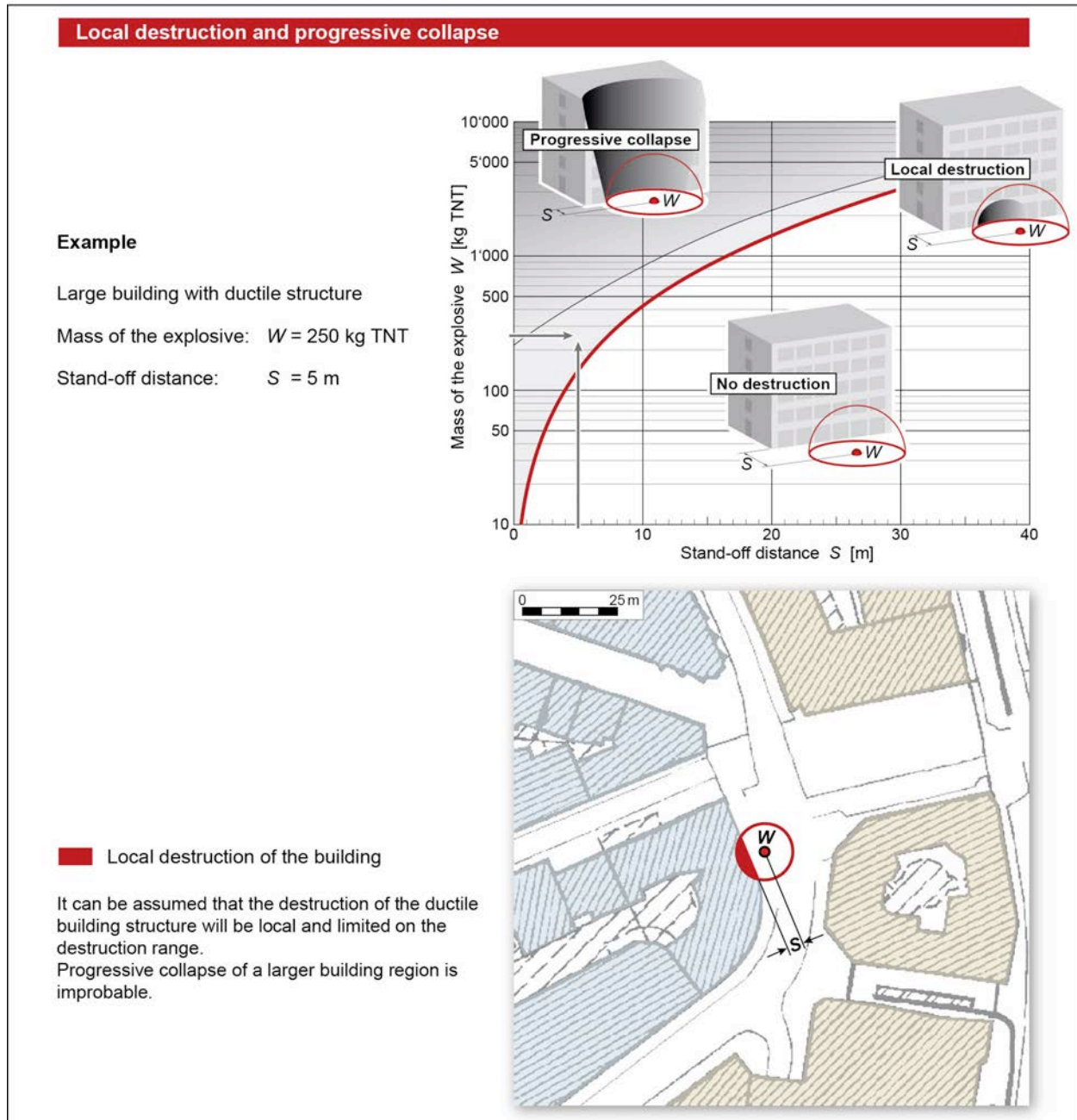


Figure 11. Practical tool and example of use: Local destruction and progressive collapse

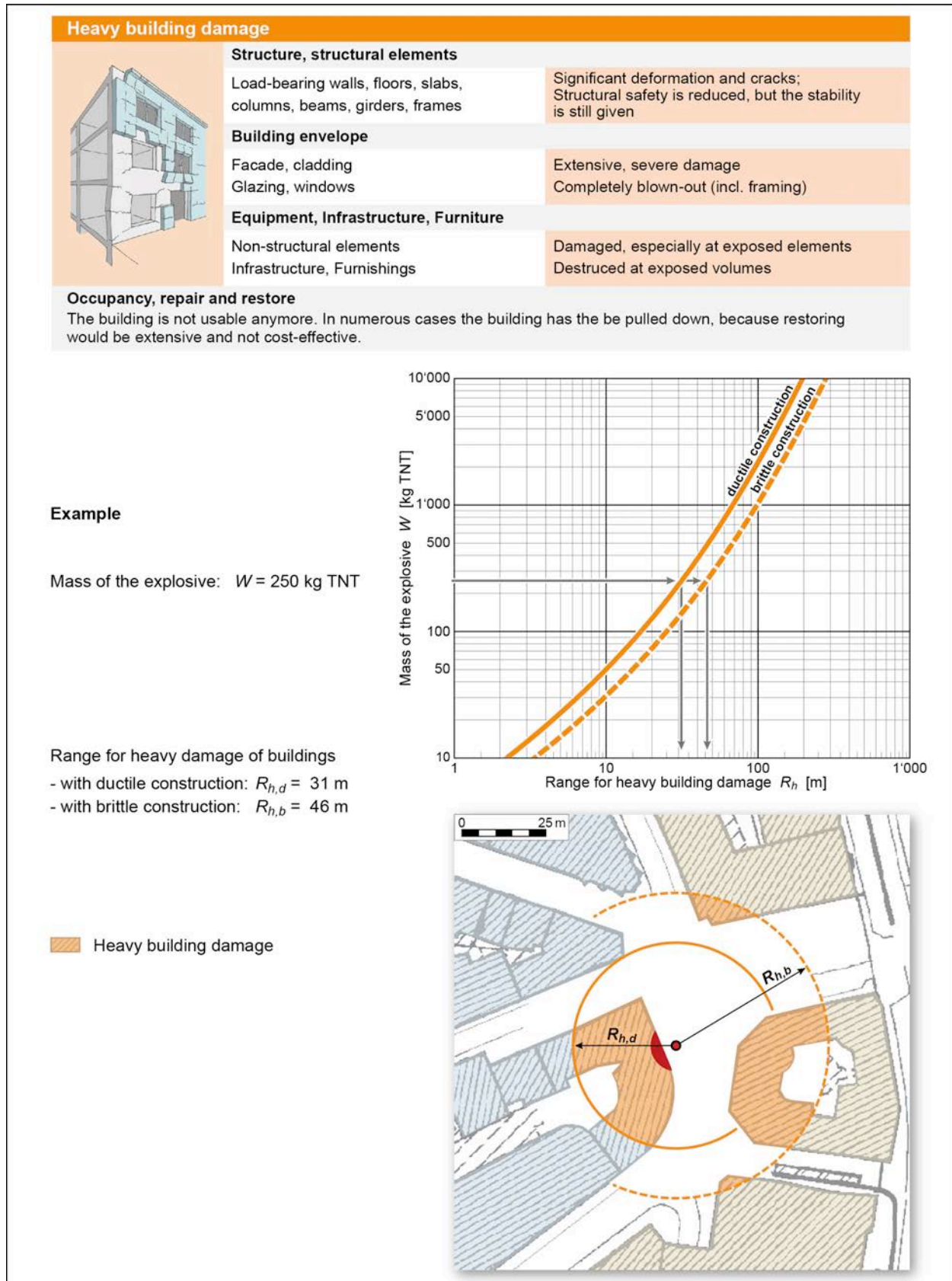


Figure 12. Practical tool and example of use: Heavy building damage

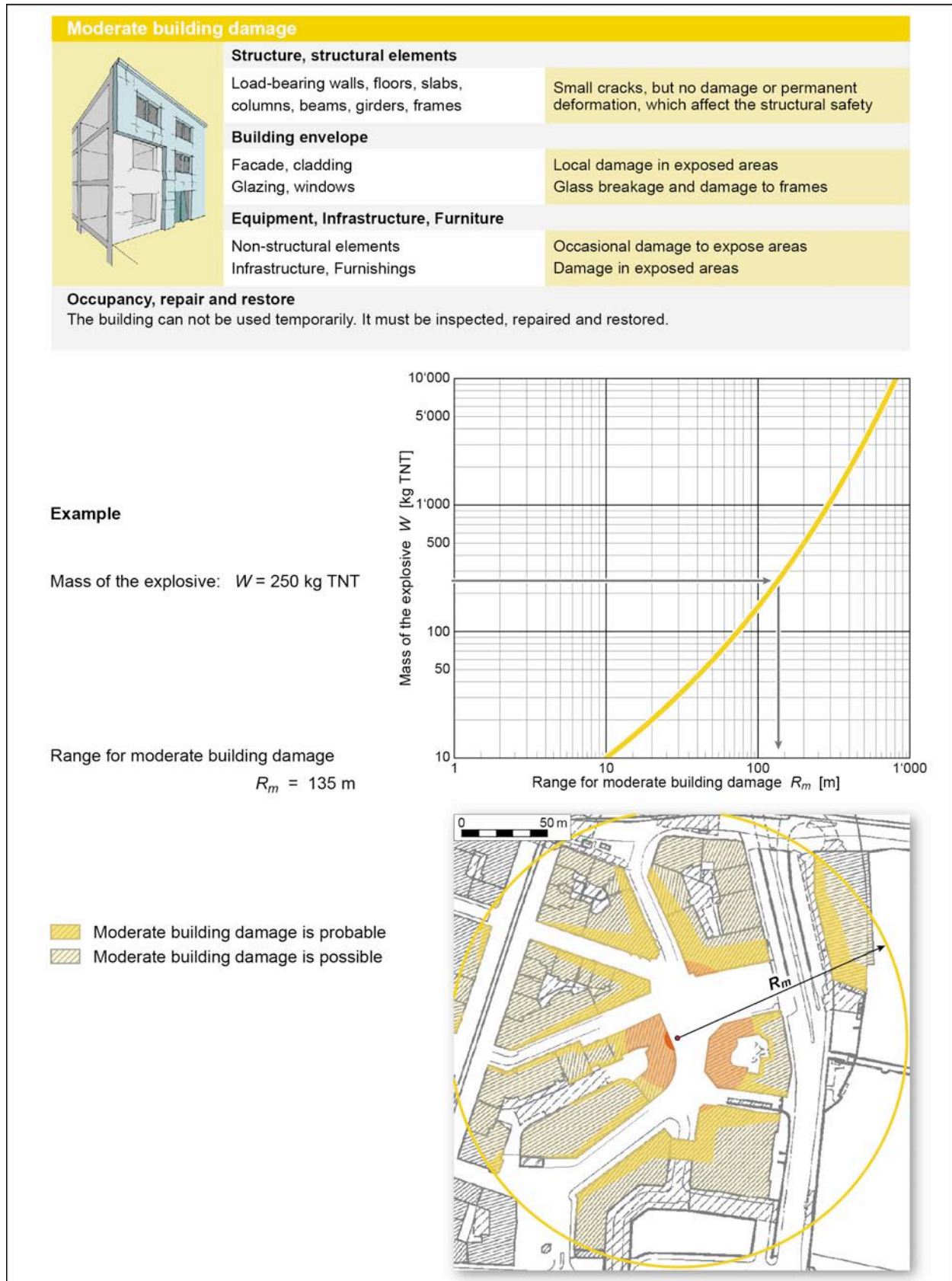


Figure 13. Practical tool and example of use: Moderate building damage

Nomenclature

i	impulse
p	peak overpressure
R	range
S	stand-off distance
W	mass of the explosive (TNT equivalent), charge

Subscripts

d	destruction
d,b	destruction of brittle structures
d,d	destruction of ductile structures
h	heavy damage
h,b	heavy damage of brittle structures
h,d	heavy damage of ductile structures
m	moderate damage
r	reflected air blast

SUMMARY

Building damage ranges due to blast effects are generally known. Often they are based on the explosion of very large charge weights e.g. nuclear explosions, thus peak overpressure of the blast is an appropriate damage criterion. In case of threats by improvised explosive devices (IED), equivalent TNT explosive weights of a few 100 kg are frequently decisive. The use of peak overpressures as damage criteria is needless conservative then because buildings, respectively their structural elements, are exposed to impulsive loadings. Since damage criteria based on $P-I$ diagrams are less transparent, the manual specifies damage ranges for building destruction, heavy and moderate building damage as well as for glazing breakage as charge-distance relationships in $W-R$ diagrams.

ACKNOWLEDGEMENT

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