REDUCING PHYSICAL VULNERABILITY TO MOUNTAIN HAZARDS BY LOCAL STRUCTURAL PROTECTION

Sven Fuchs[1], Markus Holub[2] and Jürgen Suda[3, 4]

ABSTRACT

Despite the long tradition of technical mitigation on a catchment scale in European mountain regions, losses due to mountain hazards are still considerable high in number and monetary loss. Therefore, the concept of technical mitigation had been supplemented by land-use planning and – more recently – local structural protection for buildings located in the run-out area of natural hazard processes. Implemented directly at or adjacent to endangered objects, local structural protection is able to reduce the vulnerability and additionally to be economically efficient. Nevertheless, this efficiency has so far not been quantified with respect to the overall costs necessary for the construction of buildings. Therefore, we will present a prototype of residential building typical for the Austrian Alps and adapted to mountain hazard processes. In particular, this prototype is equipped with various constructional elements which are able to resist the impact forces of hazardous events, i.e. fluvial sediment transport related to torrents, and snow avalanches. In this paper, we will focus on the constructive design necessary to resist these loads, and the amount of additional costs necessary for such an adaptation.

Keywords: mountain hazards, physical vulnerability, structural protection, risk management

INTRODUCTION

Following the axiom that natural hazard risk is a function of hazard and consequences, the ability to determine vulnerability is an essential step for reducing these consequences and therefore natural hazard risk. The approach of structural vulnerability is focusing on impact intensity and structural susceptibility of elements at risk, ranging from 0 (no damage) to 1 (complete destruction). From this point of view, vulnerability assessment is based on the evaluation of parameters and factors such as building types, construction material, state of maintenance, and presence of protection structures (Fell et al., 2008). By applying the concept of structural vulnerability, from an engineering point of view, considerable areas in European mountain regions are susceptible to hazard processes (Fuchs, 2009). Even though the theory of vulnerability has been subject to extensive research and numerous practical applications over the past decades, considerable gaps still exist with respect to standardised functional relationships between impacting forces due to occurring hazard processes and the structural damage caused (Papathoma-Köhle et al., 2011). The analysis of empirical data from torrent processes had shown that the vulnerability of buildings affected by medium hazard intensities (e.g., 1.00–1.50 m deposition height for torrent processes) is highly dependent on whether or not the entrained material harms the interior of the building (i.e., by an intrusion of material through openings such as doors, wells and windows, Fuchs, 2009; Totschnig et al., 2011). Consequently, local protection measures such as deflection walls and specially designed closure structures for at-grade openings definitely play a major role in reducing the vulnerability of buildings (Fuchs et al., 2007).

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Local structural protection measures which are implemented directly at or adjacent to endangered objects might therefore be a valuable and serious alternative with respect to reducing vulnerability within the concept of integral risk management. However, the effect of local structural protection in reducing susceptibility of values at risk has not been quantified satisfyingly so far (Holub & Hübl, 2008), even if the positive effect in reducing vulnerability seems to be obvious. Local structural protection, namely constructive preventive measures, can be either performed as enclosing structure or as structure directly connected to the building. Such enclosing structures are defined as measures surrounding elements at risk but which are not connected to them. These seem to be very effective since they prevent direct hazard impacts on the building envelope, while structures directly connected to the building envelope in principal generate an increased resistance of the construction; furthermore, they are less land-consuming. Local structural protection measures can be distinguished and classified according to their applicability for protection against hazard processes, their location with respect to the element at risk, as well as their construction type and material used. A further differentiation is according to the permanent or temporal implementation, such as permanent concrete walls or mobile flood protection. Considering the possible impacts of natural hazards, different construction materials show different performance and resistance. Consequently, a process-specific risk assessment, carried out at the earliest possible conceptual design stage and focusing on impact forces, vulnerability as well as damage patterns, will result in an appropriate protection concept. Therefore, information on both, hazard impacts and corresponding loads on the building envelope is necessary.

Taking these findings as a basis, we will present a prototype of residential building typical for European mountain regions and adapted to mountain hazard processes. In particular, this prototype is equipped with various constructional elements which are able to resist the impact forces of hazardous events, i.e. fluvial sediment transport related to torrents and snow avalanches. Therefore, we will start with a brief overview on studied hazard processes. Thereafter, we focus on (1) possible loads emerging from these hazardous processes and impacting the building envelope, (2) the constructive design necessary to resist the loads, and (3) the amount of additional costs necessary for such an adaptation.

HAZARD PROCESSES

Within this paper two major hazard categories occurring in mountain areas worldwide but also on the European level are considered: fluvial sediment transport related to torrents, and snow avalanches.

The term torrent refers to steep rivers within a mountain environment and is defined as a constantly or temporarily flowing watercourse within small catchment areas and characterised by changing perennial or intermittent discharge and flow conditions (ONR, 2009). Torrent events include a process group with a variety of different characteristics including discharge composed from pure water runoff, discharge with variable sediment concentration and debris flows. Fluvial sediment transport is characterised by a lower sediment concentration than debris floods and debris flows (< 40 % by weight, Costa, 1984). Fluvial sediment transport and related torrent processes cause static or dynamic impacts originating from flow conditions and the respective amount of transported solids. With respect to scale, process impacts may include surface as well as channel runoff, accompanied by erosion and deposition phenomena of different magnitude (Fuchs et al., 2008). The major process patterns result in possible intrusion of water and solids through the building openings and the sewage system, causing damage to the interior of the buildings, apart from possible buoyancy as well as erosion processes resulting in subsidence or even tilting, endangering the stability of the building.

Snow avalanches are fast-moving mass movements within a mountain environment and are defined as gravity-driven snow masses, moving along a certain track downwards slopes with a dislocation distance exceeding 50 m (McClung & Schaerer, 1993). According to the mechanisms of flow, snow avalanches are regularly distinguished into dense flow avalanches, which may contain additional solids such as rock fragments and logs, and powder avalanches (Keylock, 1997; Bründl et al., 2010). Elements at risk located in the deposition area are influenced by two major processes, the air pressure plume in front of a powder avalanche and the snow in motion that exerts high impact pressure on objects located in the runout path (Sovilla et al., 2008). Avalanches with their dense and powder snow part may affect buildings due to incurring high pressure loads and suction effects to the walls and the roof. Impacts originating from the dynamic or static load of snow and transported solids jeopardize the stability of the building. Furthermore, snow and solid intrusion through the building openings may occur which will lead to considerable damage inside the buildings.

In the following section, the loads resulting from fluvial sediment transport related to torrents, as well as loads resulting from snow avalanches are presented. Additionally insights in the general building design criteria are provided.

LOADS ON THE BUILDING ENVELOPE

In general, building design criteria have to rely on the following set of design loads, (1) in order to take into account the dead load of the structure; (2) to take into account the maximum possible live load; (3) load assumptions resulting from the impact of wind storm, and (4) the assumed static snow load with respect to the design criteria of the truss. Furthermore, (5) the design loads resulting from fluvial sediment transport and (6) the design loads for snow avalanches (dense part and powder part) were calculated.

(1) To take into account the dead load of the structure under consideration, the characteristic tare weights were taken from the respective Austrian building code ÖNORM B 1991-1-1 (ON, 2003, 2006a). This building code provides design guidance and actions for the structural design of buildings and civil engineering works including geotechnical aspects for the densities of construction materials and stored materials, for the self-weight of construction works, and for imposed loads for buildings.

(2) The live load of the floor slab (first and second floor) were calculated by applying ÖNORM B 1991-1-1 (ON, 2006a) with n_1 = 2.0 kN/m^2 for the category of residential buildings, n_2 = 1.5 kN/m^2 for the walkable attic story, and n_3 = 3.0 kN/m^2 for the staircase.

(3) The impact of windstorm on the structure was calculated by applying ÖNORM EN 1991-1-4 and the national specifications ÖNORM B 1991-1-4 (ON, 2005a, 2006a). The basic peak gust pressure was calculated with $q_{b,0}$ = 0.46 kN/m^2 resulting from the local wind conditions in mountain valleys of Austria. To calculate the design loads, the walls and the roof were classified into sections A to J (see Fig. 1), and different pressure coefficients c_p were assigned. With respect to the roof, the design loads 1-4 have to be calculated separately by the addition of either DL 1 and DL2, DL1 + DL 4, DL2 + DL3 or DL3 + DL4. The flow direction of the wind storm was assumed to affect the building from the valley-side. In analogy to the windstorm loads, design loads for the powder part of snow avalanches were calculated, while the flow direction of the powder part was assumed to affect the building from the hillside. In Tab. 1, the assigned pressure coefficients are shown for both, wind storm and powder avalanches (ON, 2005b). The pressure coefficients $C_{pe,10}$ are related to the probability of occurrence of a 1 in 10 years event and the exposure to a gable roof.

(4) The static snow loads and their distribution were calculated by applying ÖNORM EN 1991-1-3 and the national specifications ÖNORM B 1991-1-3 (ON, 2005b, 2006b). In dependence on the location above sea level and a specific meteorological zonation, the characteristic snow load was calculated with s_k = 2.10 kN/m^2, representing the averaged local snow conditions in Austria. The snow load on a gable roof was calculated by using Eqn. (1), the design coefficient μ_A is dependent on the inclination α of the roof and was averaged with 0.8 for an inclination of $\alpha = 30°$. Hence, the resulting snow load s_A equals 1.68 kN/m^2, while in a second set of calculations, the design load DL1 was modified to include the effect of snowdrift as shown in Fig. 2. Design load DL2 assumed a snow drift on the valley side of the roof, and for DL3 snow drift effects on the hillside were taken into account. The resulting snow loads were modified accordingly.

$$s_A = \mu_A \cdot s_k \ \text{[kN/m}^2\text{]} \qquad (1)$$

(5) and **(6)** The building envelope is affected by additional forces resulting from the impact of natural hazard processes such as fluvial sediment transport and snow avalanches. The general impact pressure of flowing masses on obstacles is based on hydrodynamic approaches following Eqn. (2). Thereby, forces resulting from the impact are considered as stationary and therefore time-independent, and flow velocities are considered as being constant over the flow depth.

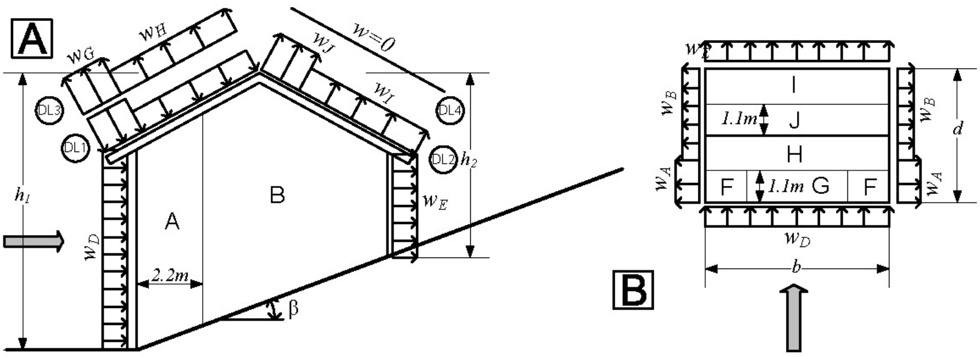

Fig. 1 Structural system for windstorm impacting a building, DL1 = load factor 1, DL2 = load factor 2, DL3 = load factor 3, DL4 = load factor 4, $w_{A...J}$ = wind load, β = inclination of the slope, $h_{1,2}$ = building height 1 and 2, d = building width parallel to the flow direction, b = building width normal to the flow direction. The grey arrow indicates the flow direction, A = lateral view, B = top view.

Tab. 1 Coefficients ($C_{pe,10}$) for the assignment of wind storm and powder avalanches loads impacting gable roofs according to ON (2006a, b), h_1, h_2, b and d refer to the building dimensions outlined in Fig. 1.

		Impact windstorm		Impact powder avalanche	
		h_1/b=0.8 und d/b=0.7		h_2/b=0.5 und d/b=0.7	
		min	max	min	max
Wall area	A	-1.04		-1.0	
	B	-0.74		-0.7	
	D	0.8		0.8	
	E	-0.37		-0.35	
Roof area	F = G	-0.5	0.7	-0.5	0.7
	H	-0.3	0.7	-0.3	0.7
	I	-0.4	0	-0.4	0
	J	-0.5	0	-0.5	0

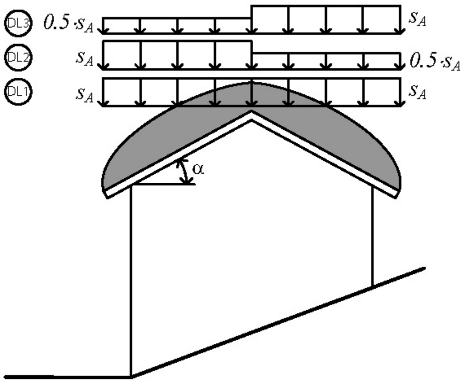

Fig. 2 Structural system for snow impacting a building, DL1 = load factor 1, DL2 = load factor 2, DL3 = load factor 3, s_A = snow load, α = inclination of the roof.

The impact of transported solids, such as woody debris and larger boulders, is considered separately due to the higher pressure which affects the building envelope locally in selected areas.

$$p = C \cdot 0.5 \cdot \rho \cdot v^2 \cdot (\sin \alpha)^2 \, [\text{kN/m}^2] \qquad (2)$$

where, ρ = density of the fluid, v = velocity of the fluid, C = resistance coefficient of the circumfluent obstacle, dependent on the type of process, the rheology of process and the geometry of the obstacle (design coefficient). The angle α is the inclination between the impacted wall (of the building envelope) and the flow direction of the hazard process. If the impacted wall is directed parallel to the flow path, an angle of $\alpha = 20°$ is used as an approximation instead to mirror the occurring forces accordingly. The impact pressure is directed normal to the impacted walls.

If any flowing masses impact an obstacle the additional resistance will increase the flow depth due the backwater effects. This increase in flow depth is approximated by Eqn. (3) for fluvial sediment transport and Eqn. (4) for snow avalanches.

$$h_{Stau} = \frac{v_{fl}^2}{2 \cdot g} \text{ [m]} \tag{3}$$

$$h_{Stau} = \frac{v_L^2}{2 \cdot g \cdot \lambda} \text{ [m]} \tag{4}$$

where, v_{fl} = velocity of the flowing mass, v_L = velocity of the snow mass, g = acceleration of gravity, λ = stowage height coefficient (dependent from flow characteristics of the fluid; dimensionless).

If areas are impacted with an angle $\alpha \neq 90°$, a friction tension (shear stress) $q_{fl,\,R}$ (fluvial sediment transport) and $S_{L,\,R}$ (snow avalanches) additionally to the normal force has to be considered (Eqn. 5 for fluvial sediment transport and Eqn. 6 for snow avalanches). Thereby, the friction coefficient μ is dependent on the roughness of the impacted wall.

$$q_{fl,R} = \rho_{fl} \cdot g \cdot h_{fl} \cdot \tan \beta \text{ [kN/m}^2\text{]} \tag{5}$$

where, ρ_{fl} = density of fluid, g = acceleration of gravity, h_{fl} = flow depth, tan β = inclination between the impacted wall (of the building envelope) and the flow direction of the hazard process.

$$s_{L,R} = \mu \cdot s_{LF,\alpha} \text{ [kN/m}^2\text{]} \tag{6}$$

where, μ = frictional loss coefficient, $s_{L,\alpha}$ = to be calculated according to Tab. 2 (overall equations used to calculate the impact pressure of fluvial sediment transport and snow avalanches are provided).

Tab. 2 Equations used to calculate the impact pressure of fluvial sediment transport and snow avalanches.

Process	Pressure	Variable	
Fluvial process	$p_{fl,dyn} = c_d \cdot 0.5 \cdot \rho_{fl} \cdot v^2 \cdot (\sin \alpha)^2$ $p_{fl,stat} = \rho_{fl} \cdot g \cdot h_{fl}$ $p_{fl} = p_{fl,stat} + p_{fl,dyn}$	c_d	Drag coefficient
Powder avalanche	$s_{LS} = c_p \cdot c_{LS}(z) \cdot 0.5 \cdot \rho_{LS} \cdot v_{LS}^2 = c_p \cdot s_{LS}(z)$	$c_{LS}(z)$	Powder avalanche coefficient (Issler, 1999)
		c_p	Pressure coefficient
Dense flow avalanche1)	$s_{LF} = c_d \cdot 0.5 \cdot \rho_{LF} \cdot v_{LF}^2 \cdot (\sin \alpha)^2$	c_d	Drag coefficient
1) Surfaces are impacted in normal direction			

Fluvial sediment transport

Design loads were based on the assumption that a building adjacent to a torrent is affected by flooding with moderate sediment load, and parameters characterising the fluvial sediment transport are shown in Tab. 3. Fluvial sediment transport results in a pressure on the luvward side (p_{fl}). The impact pressure on the walls parallel to the flow direction (K) were calculated as an area being impacted with an angle of 20° ($p_{fl20,K}$), and an additional frictional tension $p_{fl,K}$ is assumed at these walls (Fig. 3). Additionally, woody material transport was assumed at the processward building wall (q_{efl}), and was considered with a maximum pressure within an area of 0.5 x 0.5 metres.

Tab. 3 Parameters necessary to calculate the impacts resulting from fluvial sediment transport.

Parameter		Value	Source
Flow height	h_{fl}	1.0 m	Assumption
Density	ρ_{fl}	1,300 kg/m^3	(Bergmeister et al., 2008; ONR, 2009)
Velocity	v_{fl}	4.0 m/s	(ONR, 2009)
Design coefficient (rectangle)	c_d	1.50	(Egli, 1999)
Design coefficient (splitting wedge)	c_d	1.25	(Egli, 1999)

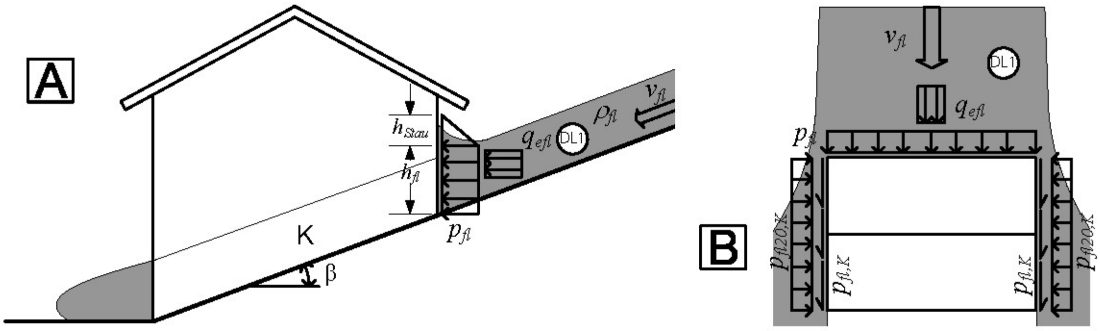

Fig. 3 Structural system for fluvial sediment transport impacting a building, DL1 = load factor 1, p_{fl} = pressure on the luvward side, $p_{fl,K}$ = frictional tension, $p_{fl20,K}$ = frictional tension assuming an impact angle of 20°, q_{efl} = impact pressure due to woody material transport, v_{fl} = flow velocity, ρ= density of the fluid, h_{fl} = flow height, h_{Stau} = backwater effects due to Eqn. (3), A = lateral view, B = top view.

The design load resulting from DL 1 is presented in Fig. 3; and the resulting impact pressures where calculated by applying Eqns. 3 and 5 based on the equations provided in Tab. 2 and the parameters shown in Tab. 3. The impact pressures resulting from the impact of fluvial sediment transport on a building were calculated with p_{fl} = 15.6 kN/m^2; $p_{fl,20,K}$ = 1.82 kN/m^2; q_{efl} = 288 kN/m^2; $p_{fl,K}$ = 4.64 kN/m^2; and h_{Stau} = 0.8 m.

Snow avalanche

Design loads were based on the assumption of a mixed-type snow avalanche hitting an obstacle, composed from a (dense) flow part and a superimposed powder part (Bründl et al., 2010). The parameters necessary for the calculation of design load are summarized in Table 4.

Tab. 4 Parameters necessary for the calculation of design loads for mixed-type snow avalanches.

Avalanche type	Parameter		Value	Source
Dense flow part	Flow depth	h_{LF}	1.5 m	Assumption
	Snowpack depth	h_A	0.5 m	Assumption
	Density	ρ_{LF}	300 kg/m^3	(ASTRA, 2007; ONR, 2007)
	Velocity	v_{LF}	20 m/s	(Bozhinskiy & Losev, 1998)
	Drag coefficient (rectangle)	c_d	2.0	(Egli, 1999)
	Drag coefficient (splitting wedge)	c_d	1.5	(Egli, 1999)
	Dimensionless coefficient due to flow characteristics	λ	1.5	(Egli, 1999)
	Friction coefficient	q	0.3	(Egli, 1999)
Powder part	Flow depth	h_{LS}	Exceeding obstacle height	Assumption
	Density	ρ_{LS}	20 kg/m³	(ON, 2006b; ONR 2007)
	Velocity	v_{LS}	40 m/s	(Bozhinskiy & Losev, 1998)
	Powder avalanche coefficient	$c_{LS}(z)$	2	(Issler, 1999)

The flow part of an avalanche causes a pressure on the luvward side of the obstacle (s_{LF}). The impact pressure on the walls parallel to the flow direction (K) were calculated as an area being impacted with an angle of 20° ($s_{LF20,\ K}$), and an additional frictional tension $s_{LR,K}$ is assumed at these walls. Additionally, potentially transported material (e.g., boulders, logs) was assumed at the processward building wall (q_{eLF}), and was considered with a maximum pressure within an area of 0.5 x 0.5 metres (Fig. 4).

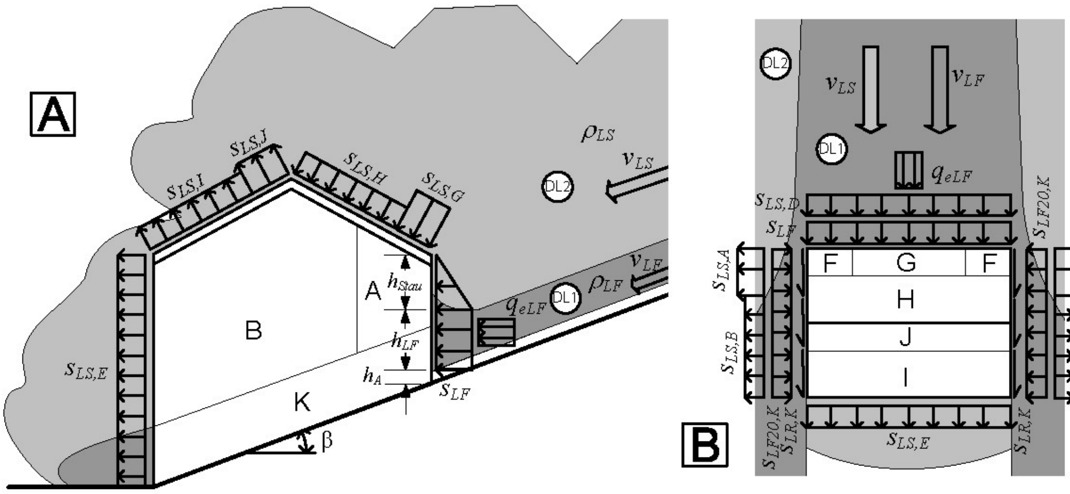

Fig. 4 Structural system for snow avalanches impacting a building, DL1 = load factor 1 (flow part) and DL 2 = load factor 2 (powder part), Flow part: S_{LF} = pressure on the luvward side, $S_{LR\ ,K}$ = frictional tension, $S_{LF20,K}$ = frictional tension assuming an impact angle of 20°, q_{eLF} = impact pressure due to woody material transport, v_{LF} = flow velocity, ρ_{LF}= density of the fluid, h_{LF} = flow height, h_{Stau} = backwater effects due to Eqn. (4), h_A = height of the initial snow cover, Powder part: $S_{LA...J}$ = load on the respective section A…J, v_{LS} = flow velocity, ρ_{LS}= density of the fluid, A = lateral view, B = top view.

The design loads resulting from DL 1 (dense flow part) and DL 2 (powder part) are presented in Fig. 4; and the resulting impact pressures where calculated by applying Eqns. 4 and 6 based on the equations shown in Tab. 2 and the parameters shown in Tab. 4, and are presented in Tab. 5. Loads incurring in the roof area ($s_{LS,G}$ – $s_{LS,J}$) were calculated by applying values from Table 2.2 following principles outlined in ÖNORM EN 1991-1-4 (ON, 2005a).

Tab. 5 Impact pressures resulting from the impact of a mixed-type avalanche on a building, values are provided in kN/m^2. h_{Stau} = 13 m.

Loads on the walls				Loads on the roof		
					min	max
s_{LF}	120	$s_{LS,A}$	-32	$s_{LS,F}$	-16	22.4
$s_{LF,20,K}$	14	$s_{LS,A}$	-32	$s_{LS,G}$	-16	22.4
q_{eF}	400	$s_{LS,B}$	-22.4	$s_{LS,H}$	-9.6	22.4
$s_{LR,K}$	4.2	$s_{LS,D}$	25.6	$s_{LS,I}$	-12.8	0
$s_{LS(z)}$	32	$s_{LS,E}$	-11.2	$s_{LS,J}$	-16	0

PROTOTYPE

Taking into account the outlined loads on the building envelope, a prototype for a contemporary reinforced building was developed representing a typical alpine residential building in the European Alps. Due to topographical constraints, residential buildings in mountain areas of Europe are commonly constructed in a hillside situation. The characteristic building includes a basement as well as first floor (ground floor) and second floor (upper floor). The average effective floor space equals 70 m^2, which amounts to approximately 210 m^2 in total. Supporting walls consist of masonry while the baseplate and the ceilings are constructed from reinforced concrete, respectively. Timber is used for the roof truss, as well as the frame connectors for windows and doors. The roof truss is covered by copper sheet; the roof area is of projecting type in order to better protect the outside walls. Due to the hillside situation, the basement serves usually as a quasi-first floor towards the valley. At the hillside, light wells are installed to allow for a utilization of the basement.

The possible loads due to hazardous events outlined before will result in several shortcomings of these typical residential buildings with respect to the design of their envelope: (1) Due to the process characteristics of fluvial sediment transport and snow avalanches, openings generally weaken the static resistance and stability of any wall. Moreover, they are a probable location for intrusion of material such as debris, water, and snow masses, above all due to the inherent material weakness of doors and windows. (2) If the material has been deposited in the interior of the building, an additional static load on ceilings and walls will occur. (3) With respect to torrent processes erosion initiated by surface runoff alongside the walls and as a result from possible shifts in the channel bed may lead to a scouring of the baseplate. (4) An overstrain of the sewage system associated with extraordinary flood discharge may cause back water effects in the sewage pipes of the building and, as a result, cause flooding from inside. (5) With respect to snow avalanches, a projecting roof is considerable susceptible to damage due to the occurring pressure gust and suction effects which result from the velocity of the powder part of the avalanche.

As a consequence, a necessary mitigation concept has to be developed taking into account these shortcomings. Local structural protection can be performed either in terms of a structural reinforcement of an existing building envelope, or in terms of a construction design comprehensively adapted to possible loads of a new construction. Thereby, constructive measures can either be physically connected to the building envelope (e.g., a reinforced window shutter), or the envelope as a whole could be adopted (e.g., by removing any window openings at the exposed building side). However, the overall aim is to develop a cost-efficient and protection-effective solution (Holub & Fuchs, 2008) that simultaneously fulfils the requirements of a formal aesthetic standard.

Structural reinforcement of the building

The structural reinforcement of any building in terms of increased protection against the impact of natural hazard processes (i.e., fluvial sediment transport and snow avalanches) can be achieved by different constructive approaches. In this section, possible adaptations will be presented with respect to reinforcement of the foundation, the structural levels (first and second floor), the roof construction, as well as with respect to additional design elements such as building openings, or mobile protection elements (see Tab. 6 and Fig. 5). A comprehensive matrix of necessary adaptations, including cost calculation, can be requested from the authors.

A major protective effect regarding possible settlements of the entire building, which may occur due to erosion originating from torrent processes, includes the construction of a base plate instead of a strip foundation; a measure that is obviously suitable to increase the overall stability. Furthermore, the basement should be waterproofed by a sealed type of construction obtained by the use of waterproofed concrete, including the sealing of penetration such as pipes and infrastructure facilities. Light shafts implemented should exceed the expected possible flood level in order to prevent the intrusion of liquids and solids into the interior. Moreover, a backflow flap installed in the sewage system effectively prevents against the effects of possible capacity overload of the drainage. The first floor is particularly susceptible to any type of external impact resulting from torrent processes and snow avalanches, i.e., the additional dynamic as well as static pressure towards the outer walls caused by the medium, and pressure peaks originating from transported solid particles (woody debris, boulders). Therefore, process-side outer walls should be either retrofitted in case of existing structures (e.g., by an additional concrete shall) or constructed from reinforced concrete instead of brick masonry in case of a new construction. With respect to the roof construction, eaves should be avoided to increase the resistance of the structure against pull resulting from avalanche processes. Furthermore, an overall strengthening is recommended to resist heavy snow loads, however, this is regularly prescribed in the local building codes.

As an overarching framework, any building openings should be avoided on the process-oriented (impacted) building walls. If this is not possible due to architectural or aesthetical constraints, the building openings have to be reduced in number and size, and any openings at ground surface level should be eliminated. If necessary, specially reinforced multilayer window glass, window frames and fittings are available to protect against the considerable impact pressure of hazard processes, i.e., snow avalanches. A combination with window shutters mounted at the exterior of the wall instead within the window frame complements these suggestions.

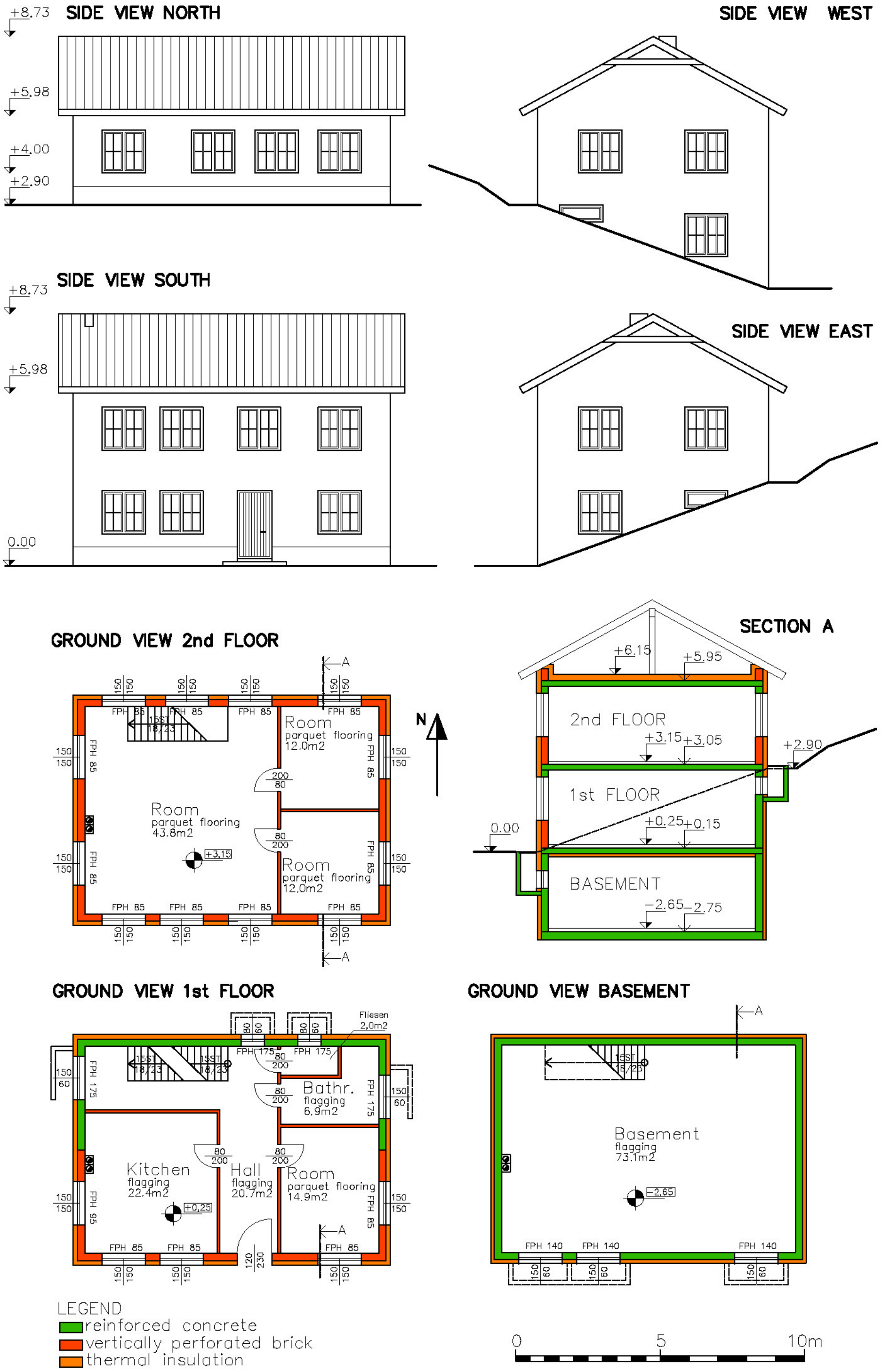

Fig. 5 Prototype building representing a typical reinforced alpine residential building.

Tab. 6 Possible local structural mitigation measures for a reinforcement of the building, the effectiveness is indicated by x = very effective, (x) = effective and - = not effective; and the suitability for the upgrading of existing buildings is indicated similarly.

Local structural protection measure	**Type of measure**	**Effective for**		**Suitable for**	
		Avalanche	**Flood**	**Upgrade**	**New building**
Foundation	Base plate foundation	(x)	x	-	x
Basement	Waterproofed concrete	-	x	-	x
	Enhancement (raising) of light shafts above flood level (flow depth), sealing of all wall penetrations	(x)	x	x	x
	Backflow flaps in sewage pipes	-	x	(x)	x
First (and second) floor	Reinforcement of the supporting structure (walls, ceilings, …)	x	x	(x)	x
Roof	Reinforcement of the roof, avoidance of eaves	x	-	(x)	x
Building openings	Decrease of the amount and area of windows and implementation of avalanche safe windows and/or heavy shutters	x	(x)	x	x

EXPENSES NECESSARY FOR LOCAL STRUCTURAL PROTECTION

Within this section, a prototype of residential building adapted to mountain hazard processes is presented based on the design needs outlined above. This prototype is based on the modern residential building typical for the European Alps and is equipped with various constructional elements which are able to resist the impact forces of hazardous events, i.e., fluvial sediment transport, and snow avalanches. The amount of construction costs are opposed to the additional expenditures necessary for an adapted design. The price basis is related to the average standard construction prices in Austria, which equals approximately the price indices in European mountain regions. The sets of calculation are based on net prices and neglected the sales tax; therefore, the results are in principle applicable to other countries with different taxation systems. A comprehensive overview on absolute prices used for the sets of calculation can be requested from the authors.

Tab. 7 Relative increase in construction costs if local structural mitigation is implemented.

Measure	**Δ construction costs (compared to standard version) [%]**
Reinforcement of the hillside outer wall	+ 17
Reinforcement of the structural slab	+ 30
Reinforcement of the truss	+ 10
Reduction of eaves (decrease in roof area)	- 16
Avalanche-proof window and window shutter	+ 67
Above flood-level light shafts	+ 23
Total costs of the prototype building	**+ 8**

Due to the design loads necessary for the implementation of different local structural protection measures, the average construction costs are above the costs for unprotected buildings. Nevertheless, the ratios differ for individual measures as shown in Tab. 7. While the additional expenditures for the construction of a structural slab amount to an increase of one third, and the implementation of avalanche-proof windows result in an increase of two thirds (calculated in terms of the individual costs needed for this respective measure), the reduction of eaves leads to a decrease in construction costs of approximately 16 %. In total, the design adaptation of the prototype building under consideration lead to an increase in construction costs of 8 %, compared to an unprotected standard building.

CONCLUSION

Neither conventional structural measures, which influence both, the magnitude and frequency of events, nor passive mitigation concepts can guarantee reliability and complete safety of elements at risk exposed. Therefore, the concept of local structural protection was developed (Egli, 1999; Holub & Hübl, 2008). This concept has been proven to be very cost-efficient; above all, since the required expenditures do not necessarily have to taken over by the general public (Holub & Fuchs, 2009). However, until now only little information was available on the absolute height of investments needed for such measures on the local scale.

Taking these findings as a basis, a prototype of residential building typical for European mountain regions has been presented. Based on possible design loads, this prototype was further equipped with different local structural protection measures in order to resist the impact forces of torrent hazards and snow avalanches. The underlying structural modifications were calculated based on information from the Austrian construction industry and the insurance business. As a result, it had been shown that the adaptation of the standard building would result in an increase in construction costs of below 10 %. In absolute number, the increase in construction cost due to the implementation of structural mitigation outlined above amounts to approximately € 17,000. If this amount is compared to available data related to direct losses resulting from torrent events and snow avalanches, the savings potential becomes obvious (e.g., Fuchs, 2009; Hilker et al., 2009). Comparing the results of our study with such data clearly proved the potential for local structural protection; depending on the data set, an investment of approximately € 17,000 is at least able to prevent the effects of low-magnitude but high-frequency torrent processes (amounting to € 8,000 on average, Oberndorfer et al., 2007). With respect to higher-magnitude torrent events, it has to be assumed that at least a considerable portion of the average of € 85,000 per damaged building (Fuchs, 2009) will be prevented, and a respective decrease in loss has to be assumed. With respect to snow avalanches, the investment in local structural protection equals the average loss (Fuchs & Bründl, 2005), which in turn implies that such average loss can be effectively prevented by local structural protection.

Within the overall context of managing natural hazard risk, local structural protection aims at reducing the structural vulnerability of buildings exposed due to a reduction of design loads on the building envelope and due to a prevention of material intrusion through building openings protected. As a result, the resilience towards low-magnitude and high-frequency events can be enhanced, leading to less economic vulnerability of values at risk exposed (Fuchs, 2009). An increased economic resilience, in turn, will discharge the public funds necessary, since due to missing overarching insurance systems in Austria the competence of compensating losses that incurred due to natural hazards is allocated on the level of federal states (Holub & Fuchs, 2009).

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