# RESEARCH

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# Impact resistance of steel materials to ballistic ejecta and shelter development using steel deck plates



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# Abstract

The destruction caused by ballistic ejecta from the phreatic eruptions of Mt. Ontake in 2014 and Mt. Kusatsu-Shirane (Mt. Moto-Shirane) in 2018 in Japan, which resulted in numerous casualties, highlighted the need for better evacuation facilities. In response, some mountain huts were reinforced with aramid fabric to convert them into shelters. However, a number of decisions must be made when working to increase the number of shelters, which depend on the location where they are to be built. In this study, we propose a method of using high-strength steel to reinforce wooden buildings for use as shelters. More specifically, assuming that ballistic ejecta has an impact energy of 9 kJ or more, as in previous studies, we developed a method that utilizes SUS304 and SS400 unprocessed steel plates based on existing impact test data. We found that SUS304 is particularly suitable for use as a reinforcing material because it has excellent impact energy absorption characteristics due to its high ductility as well as excellent corrosion resistance. With the aim of increasing the structural strength of steel shelters, we also conducted an impact test on a shelter fabricated from SS400 deck plates (i.e., steel with improved flexural strength provided by work-hardened trapezoidal corrugated plates). The results show that the shelter could withstand impact with an energy of 13.5 kJ (2.66 kg of simulated ballistic ejecta at 101 m/s on impact). In addition, from the result of the impact test using the roof-simulating structure, it was confirmed the impact absorption energy is further increased when artificial pumice as an additional protective layer is installed on this structure. Observations of the shelter after the impact test show that there is still some allowance for deformation caused by projectile impact, which means that the proposed steel shelter holds promise, not only structurally, but also from the aspects of transportation and assembly. Hence, the usefulness of shelters that use steel was shown experimentally. However, shelter construction should be suitable for the target environment.

**Keywords:** Impact, Ballistic ejecta, Phreatic eruption, Impact-resistant design, Stainless steel, Trapezoidal corrugated plate

# Introduction

The phreatic eruption of Mt. Ontake, which is located along the border of Gifu and Nagano Prefectures in Japan, that occurred on September 27, 2014, killed

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numerous hikers close to the summit (58 people died and 5 people are missing). The main cause of death was injury due to volcanic blocks and lapilli (hereafter collectively referred to as ballistic ejecta) (Oikawa et al. 2015; Kaneko et al. 2016; Oikawa et al. 2016). In the phreatic eruption of Mt. Kusatsu-Shirane (Mt. Moto-Shirane) in Gunma Prefecture on January 23, 2018, ballistic ejecta directly struck and killed one Japan Ground

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Self-Defense Force member during training (Terada et al. 2018; Yoshimoto et al. 2018). The fatal injuries caused by ballistic ejecta impact in recent years have highlighted the difficulties of coping with volcanic hazards, especially those caused by phreatic eruptions. Phreatic eruptions can occur unpredictably and suddenly, which is extremely dangerous for hikers. For volcanoes, the most effective safety measures are the designation of restricted areas and hazard warnings. However, in Japan, where scenic volcanoes are major tourist destinations, the key challenge is to devise measures against sudden unexpected phreatic eruptions. The development of technology that can mitigate ballistic ejecta impact damage is thus a pressing issue. A previous numerical simulation of the Mt. Ontake eruption suggests that ballistic ejecta 200 mm in diameter were ejected at a velocity of 145–185 m/s (Tsunematsu et al. 2016). With an average velocity at impact of 83-85 m/s, such a ballistic would be fatal if it struck a human (Baxter and Gresham 1997). However, most of the ballistic ejecta scattered during the eruption of Mt. Ontake in 2014 were approximately 100 mm in diameter, as determined by fieldwork surveys taken on August 19 and 20, 2015, in a joint survey of the Japanese Coordinating Committee for Prediction of Volcanic Eruptions (Disaster Management, Cabinet Office 2015a, 2015b). The damage caused by the ballistic ejecta appears to have been primarily caused by ballistics mainly 100 mm in diameter. The handbook on shelters published by the Disaster Management of the Cabinet Office of Japan, which is described in detail later, was prepared based on the results of this survey. After the handbook was published, Japanese shelters have standards to withstand the impact of ballistic ejecta of 100 mm in diameter at 83 m/s.

Phreatic eruptions can produce projectiles over 1 m diameter (e.g. Fitzgerald et al. 2014). However, in this study, we focus on ballistic ejecta of 100 mm in diameter reported in the field survey as well as previous studies (Yamada et al. 2018) of the phreatic eruption of Mt. Ontake in 2014.

A large number of people were injured due to ballistic ejecta when Mt. Ontake erupted, mainly because of the high number of hikers on a Saturday during autumn. The absence of shelters and facilities along the mountain trails and at the summit is also believed to have been a factor. There are several mountain huts near the top of Mt. Ontake, and none of the hikers who took refuge within them died (Yoshimoto 2015). This suggests that the huts can be used as emergency shelters during sudden eruptions. However, ballistic ejecta did considerable damage to the huts (e.g., it penetrated the roofs and damaged the walls), so it is fortunate that there were few injuries among the people taking refuge within them (Yoshimoto 2015). If mountain huts are to be designated for use as evacuation facilities, it is essential to improve their impact resistance to ballistic ejecta.

In a previous study, the authors experimentally demonstrated that two layers of an aramid fabric (Toray Kevlar<sup>®</sup> fabric: FS3300) placed between a waterproof sheet and the roof boards of an existing mountain hut could withstand ballistic ejecta impacts with an energy of about 13 kJ (mass of 2.66 kg at 100 m/s (360 km/h)) (Yamada et al. 2018). Although it was not possible to continue the experiment until penetration occurred because of the limited capacity of the experimental equipment, the results showed that roofs protected in this manner could withstand very high energy levels. Some of the results were published in the Handbook for Improving Volcanic Shelters (hereafter referred to as the handbook) (Disaster Management Bureau, Cabinet Office 2015a, 2015b). Aramid fabric is lightweight; FS3300 aramid fabric is  $0.6 \pm 0.1$  mm thick and weighs 0.45 kg/  $m^2$ . Because the fabric can be carried by a person, it is a suitable reinforcement material for high-altitude mountain huts where the only options for transporting heavy objects involve helicopters or other specialized equipment. Furthermore, even if helicopters are used, transportation costs are lower than those for metal or concrete. Although aramid fabrics have to be rigidly fixed using bolts to ensure that they do not come off when impacted by ballistic ejecta, this can be done without heavy equipment.

Table 1 and Fig. 1 show the development status of shelters in Japan as of August 2020 after the publication of the handbook. As shown, many mountain huts and visitor centers have already been reinforced with aramid fabric. In particular, a significant number of aramid fabric reinforcements were performed after the eruption of Mt. Ontake, reflecting the high level of awareness in disaster-affected municipalities. However, considering the 111 active volcanoes in Japan, the spread of aramid fiber fabric reinforcement is still far away. This is due to the problem that aramid fiber fabrics are very expensive and cannot be easily introduced. Therefore, in order to promote the reinforcement of the current mountain huts, it is necessary to study a method that can provide a certain level of reinforcement at a lower cost without requiring high performance up to aramid fiber fabric. In addition, in some cases, aramid fabric was also used in locations easily accessible by heavy equipment. Note that reinforced concrete (RC) and steel structure shelters were also built.

The handbook recommends the installation of RC shelters using arch and box culverts, among others, in places where heavy construction work can be carried out. Numerous studies have reported on the excellent impact resistance of RC shelters to flying and falling objects (e.g., Ito et al. 1991). Hence, even though a specific

**Table 1** Development status of evacuation facilities after publication of the handbook for improving volcanic shelters by the Disaster Management of the Cabinet Office of Japan (as of August 2020). The numbers in the table correspond to those shown in Fig. 1

No.	Volcano name	Facilities	Structure and reinforcement method	Distance from crater (m)	Crater used for measurement
1	Mt. Tokachi-dake	Emergency evacuation facility	Reinforced concrete (RC) construction	3400	62–2 crater
2	Mt. Akita- yakeyama	Mountain hut: Yakeyama emergency hut	Wooden building reinforced with aramid fabric	200	Onigajyo
3	Mt. Iwate	Mountain hut: Eighth station's emergency shelter	Wooden building reinforced with aramid fabric	750	Omuro crater
4	Mt. Azuma	Visitor Center	Steel frame building reinforced with aramid fabric	700	Ooana crater
5	Mt. Nasu	Mountain hut: Minenochaya ruins emergency hut	Wooden building reinforced with aramid fabric	650	West side slope of Chausudake
6	Mt. Kusatsu- Shirane	Emergency evacuation facility	RC construction	1000	Near center of crater chain of 2018 Mt. Moto-shirane eruption
7	Mt. Niigata- Yakeyama	Mountain hut: Koyaike Hutte	Steel frame building reinforced with aramid fabric	4650	Summit Crater
8	Mt. Tateyama, Midagahara	Mountain hut: Raichoso	Steel frame building reinforced with aramid fabric	400	Jigokudani
9	Mt. Norikura	Mountain hut: Katanokoya	Wooden building reinforced with aramid fabric	950	Kengamine
10	Mt. Ontake	Emergency evacuation facility	RC construction	450	Near center of 2014 crater chain
		Emergency evacuation facility	Steel structure	550	
		Mountain hut: Kitosho (prayer room)	Wooden building reinforced with aramid fabric	450	
		Mountain hut: Ninoike shinkan		1000	
		Mountain hut: Ninoike Hutte		1050	
		Mountain hut: Ishimuro sanso		1050	
		Mountain hut: Gonoike goya		2250	
		Mountain hut: Otaki Chojo emergency hut		550	
		Mountain hut: Ninth station's emergency hut		700	
		Mountain hut: Eighth station's emergency hut		1400	
11	Mt. Hakone	Emergency evacuation facility	RC construction	200	Crater of 2015 eruption
		Emergency evacuation facility	Steel structure	400	
12	Mt. Kirishima	Visitor Center	Wooden building reinforced with aramid fabric	950	Mountain peak of Mt. Io



impact resistance to ballistic ejecta from a volcanic eruption has not been clearly specified, many RC shelters have been set up in the vicinity of active volcanoes such as Mt. Aso, Mt. Sakurajima, and Mt. Kirishima in the Kyushu region in Japan (Erfurt-Cooper 2010; Fitzgerald et al. 2017). Williams et al. (2017) recently conducted experiments that simulated ballistic ejecta impacts on RC shelters and provided more realistic safety design guidelines based on empirical reliability. Furthermore, studies have shown that the safety of RC shelters can be increased by reinforcing them with highperformance fabric adhesion (Beppu et al. 2012) to prevent back surface scabbing from occurring during highspeed impacts (Hughes 1984; Ito et al. 1995), which is an issue for RC structures, and by layering them with cushioning materials such as sand, gravel or tephra (Bhatti and Kishi 2010; Bhatti 2015; Yamaguchi et al. 2015; Williams et al. 2019).

Although setting up RC shelters as measures against ballistic ejecta impact seems like a simple solution, the above studies show that the total cost, which include the costs of the RC shelter, installation, and material transportation, can be very high. Additionally, it is not possible to set up such shelters within the ballistic hazard zone (< 5 km from the vent) of every volcano. Moreover, it would be difficult to set up RC shelters at World Heritage Sites and in National Parks, such as Mt. Fuji, and other areas with landscape restrictions, even if heavy construction could be carried out without incurring high transportation costs. In these cases, the best solution is to reinforce existing mountain huts. An affordable reinforcement material is thus needed. Considering the need for more impact-resistant shelters against ballistic ejecta, we herein report on the development of a reinforcement method for wooden buildings and shelters that is different from conventional methods (Yamada et al. 2018; Yamada et al. 2019).

To provide better evacuation facilities, reinforcement materials that are compatible with the target location must be selected. With this in mind, to increase the available options, we propose the use of easily available and relatively inexpensive steel materials. Temporary shelters made of steel have been installed at construction sites around active volcanoes in Japan, as shown in Fig. 2. Steel shelters are considered optimal for temporary evacuation because they are easy to assemble and disassemble. In addition, as known from the damage to the gondola lift caused by ballistic ejecta impact in Mt. Moto-Shirane eruption (Kanagawa Shimbun 2018), there are also many structures made of steel materials around the active volcanoes. However, we did not find any safety design criteria for their impact resistance to ballistic ejecta. Additionally, to the best of our knowledge, steel shelters to protect against volcanic ballistic ejecta have not been constructed outside Japan. There are no reports that quantitatively discuss the suitability of steel materials for shelters. Therefore, to evaluate the impact resistance of ballistic blocks to steel materials, this study uses the results of impact tests on existing steel materials that the authors had previously conducted (Yamada et al. 2016; Fukui et al. 2017). Due to the effects of volcanic gases such as sulfur dioxide (SO<sub>2</sub>) and hydrogen sulfide (H<sub>2</sub>S) in the vicinity of such shelters, we chose stainless steel plates, which have high corrosion resistance, as our first candidate material, and analyzed structural steel plate data to propose a simple mountain hut reinforcement against ballistic ejecta that did not use aramid fabric. Moreover, it is not necessary to rely solely on the strength of the material itself to suppress the bending deformation that occurs at the time of ballistic ejecta impact because steel can be fabricated into different shapes, making it possible to fabricate structures with high flexural strength. For example, the corrugated plate shown in Fig. 2b is superior in strength to a flat plate of the same material, and its usage is expected to enhance the structural strength of the shelter. Therefore,



as a structure with even higher strength, we experimentally studied the applicability of using trapezoidal corrugated deck plates on shelters. In addition, the effect of emplacing pumice on this structure was also examined.

# Mountain hut roof reinforcement using steel materials (application of previous study results) Candidate reinforcement materials

Numerous experimental studies examining the impact of projectiles on steel plates have been conducted (Chiba et al. 1981; Ohte et al. 1981; Børvik et al. 1999; Kpenyigba et al. 2013). The Manual on Design, Construction and Maintenance for Steel Roofing and Wall (MSRW2014) (Japan Metal Roofing Association, Japanese Society of Steel Construction 2014), in which countermeasures against projectiles driven by strong winds impacting steel plates are considered, has recently been published in Japan. Moreover, research on abrasive collision safety for grinding machine covers made of steel (SUS304 and SS400) has also been conducted and the data obtained have been used in proposals of international standards (Yamada et al. 2016; Fukui et al. 2017). These studies show the results of impact tests carried out on steel plates in a wide range of engineering fields, including nuclear, architectural, and mechanical engineering.

Metallic materials installed on active volcanoes often suffer from corrosion caused by volcanic gases. Previous studies that employed experimental conditions simulating actual volcanic environments to examine the extent of volcanic gas corrosion that occurs when volcanic ash adheres to metallic materials have revealed that the amount of volcanic ash affects the extent of volcanic gas corrosion (Izumo et al. 1990; Oze et al. 2014). However, details of how metallic materials are corroded by longterm exposure to low volcanic gas concentrations in environments accessible to hikers and tourists are unknown.

In this study, stainless steel and conventional steel plates, which are in widespread general use, were selected as candidate reinforcing materials for use in resisting ballistic ejecta. For the stainless steel plate, we used SUS304 (which is defined in the Japan Industrial Standards (JIS) as G 4305:2012) because it is in widespread use in Japan. (Note that this material is referred to as 4301–304-00-I in the International Organization for Standardization (ISO) 15,510:2014 standards). The primary chemical composition of SUS304, a typical austenite stainless steel, contains 18% Cr and 8% Ni. Due to its excellent corrosion resistance, ductility, weldability, and strength, it is widely used in engineering, from household goods to nuclear equipment. In this study, we considered SUS304 as our first candidate material

because of its superior corrosion resistance compared to that of other steel materials.

For the conventional steel plate, we used rolled steel for general structures SS400 (JIS G 3101:2015), which is widely marketed in Japan because of its many shape and size options as well as its versatility and affordability. The numbers following SS represent the lower limit of tensile strength (maximum stress during a tensile test). For SS400, the tensile strength ranges from 400 to 510 MPa. There are no specifications regarding the detailed chemical composition, such as carbon content. Furthermore, there is no equivalent product for SS400 in ISO 630 for steel materials, although E275A, E275B, E275C, and E275D match its tensile strength. Without surface treatment, the corrosion resistance of SS400 is very poor compared to that of SUS304. Note that the SS400 used in this experiment was not surface-treated.

Figure 3 shows the nominal stress-strain ( $\sigma$ – $\varepsilon$ ) relationship for SUS304 and SS400 reported in previous studies (Yamada et al. 2016; Fukui et al. 2017). Table 2 shows the chemical composition of SUS304 and SS400. Specimens of these materials were made from the same lot as that used for the plate used for the impact test described later. The data (Yamada et al. 2016; Fukui et al. 2017) are the results of quasi-static tensile tests (strain rate from  $10^{-4}$  to  $10^{-2}$  s<sup>-1</sup>) conducted using a commercially universal testing machine (Instron, 5500R) and high strain rate tensile tests (strain rate from  $10^{2}$  to  $10^{3}$  s<sup>-1</sup>) conducted using the split-Hopkinson pressure bar method (Institute of Space Dynamics, ST-R-5000) (Hopkinson 1914; Kolsky 1949).

For the impact tensile test, complete data (i.e., until fracture) could not be collected due to the limited capacity of the testing apparatus (arrows in Fig. 3). The figure shows that SUS304 is a more highly ductile material with a larger fracture strain than SS400. Moreover, at the early stages of deformation, it can be seen that the flow stress clearly increases as the strain rate increases for both materials, indicating a positive strain rate dependence of material strength. However, for SS400, the flow stress does not increase significantly with increasing strain (i.e., the work-hardening rate is low) at the high strain rate used in the test, which is considered to be close to the strain rate during the impact test. In contrast, the high-strain-rate data for SUS304 shows a work-hardening rate that is similar to that for the quasistatic tensile test, which indicates high flow stress until fracture.

# Impact energy of steel materials based on previous results

As described above, the authors previously reported the results of abrasive (projectile material) impact tests on SUS304 (Fukui et al. 2017) and SS400 (Yamada et al.



2016) in grinding machine cover safety evaluations. These results are from tests carried out using exactly the same abrasive, device, and method as those used in previously reported reinforcement experiments (impact tests) on mountain huts (Yamada et al. 2018). One point where the experimental conditions differ is in the length of the projectile used, which was changed from 170 to 220 mm (weight: 3.4 kg). Nevertheless, in the present study (as in previous experiments), because the impact surface area is the same (90 mm in diameter), the kinetic energy of the projectile could be compared by considering it as impact energy.

Figure 4 shows the relationship between the impact energy and the plate thickness for SUS304 and SS400. In this figure, the point where the steel plate fractures and is penetrated is indicated by ×, that where the steel plate fractures but is not penetrated through by the projectile (projectile is stuck in the steel plate) is indicated by  $\Box$ , and that where the whole plate undergoes plastic deformation only without fracturing is indicated by  $\circ$ . Because the data indicated by  $\Box$  are the critical energy that defines the boundary between fractured and unfractured steel plates, this value is defined as the penetration boundary energy ( $E_p$ ). It can be seen that the penetration boundary energy for SUS304 is higher than that for SS400. Impact energy absorption U (J/m<sup>3</sup>) can generally be expressed by the following equation.

$$U = \int \sigma d\varepsilon \tag{1}$$

 Table 2
 Main chemical constituents of SUS304 and SS400 (mass%)

Chemical component	С	Si	Mn	Р	S	Ni	Cr
SUS304	0.06	0.57	1.03	0.03	0.00	8.07	18
SS400	0.11	-	0.47	0.01	0.00	-	-

It is evident from the above equation that the impact energy absorption increases as the stress ( $\sigma$ ) and ductility ( $d\epsilon$ ) increase. Consequently, SUS304, which has higher flow stress and higher ductility than those for SS400, shows excellent impact energy absorption.

Based on the impact test results, the relationship between the penetration boundary energy  $(E_p)$  and the plate thickness (*t*) can be expressed by the following equation for both SUS304 and SS400.

$$E_n = kt^2 \tag{2}$$

where k is a material constant. Eq. (2) estimates the energy to be proportional to the square of the plate thickness assuming a rigid perfectly plastic material and considering a model with local bending (hinge) at the outer edge of the impact surface (Yamada et al. 2016).



**Fig. 4** Relationship between impact energy and plate thickness for SUS304 (Fukui et al. 2017) and SS400 (Yamada et al. 2016). The dashed lines represent the relationship between the penetration boundary energy and the plate thickness. The dotted line indicates the modelled impact energy of 9 kJ for 128 mm diameter, spherical ballistic ejecta (2.66 kg at approximately 83 m/s on impact) that were ejected during the Mt. Ontake eruption in 2014. As shown, for a given plate thickness, SUS304 is superior to SS400 in terms of impact resistance

### Comparison of steel plate and aramid fabric

Table 3 shows a comparison of the results for a steel plate and aramid fabric. We compared the mountain hut reinforcement methods using SUS304, SS400, and aramid fabric (previous study). For a maximum impact energy of the ballistic ejecta of 9 kJ, the thickness of the steel plate calculated using Eq. (2) is 1.36 mm for SUS304 and 2.55 mm for SS400. Because there are no standards with these thicknesses, we considered sizes that are generally sold throughout Japan, using t = 1.5 mm ( $E_p \approx 11$  kJ) for SUS304 and t = 3.2 mm ( $E_p \approx 14$  kJ) for SS400. Two layers of aramid fabric are necessary, as discussed in a previous paper (Yamada et al. 2018).

We regarded mass as an important consideration in the transportation and construction necessary for reinforcement. In terms of mass per unit area (kg/m<sup>2</sup>), SUS304 and SS400 are much heavier than aramid fabric, as shown in Table 3. The construction of mountain huts has to be reconsidered when using steel plates. Furthermore, because SS400 has poor corrosion resistance, the use of stainless steel plates (e.g., SUS304) is recommended. If SS400 is used, it is necessary to apply paint to improve corrosion resistance. However, evaluation of corrosion resistance to volcanic gas is an issue for the future.

If construction cost is taken into consideration, the primary factor is the price of materials. In Japan, reinforcement with SUS304 can be performed at around half the price of that with aramid fabric (rough estimate for 200  $m^2$  of roof, as the price varies depending on the amount of material used). Additionally, taking the construction period into consideration, a large number of work days are required for reroofing when using aramid fabric, whereas SUS304 can be installed in a short period of time because it can be attached on top or installed in lieu of a Galvalume steel plate. Therefore, considering the cost of materials and the construction period, SUS304 may be more affordable than aramid fabric. However, transportation cost is a major factor, and thus

the reinforcement operation should be suitable for the target environment. Specifically, SUS304 should be used for locations where construction is easy and cranes can be employed, whereas aramid fabric should be used for locations where construction is difficult, such as on high-altitude volcanoes that would typically require helicopter transport for the materials.

# Impact resistance to ballistic ejecta of steel deck plates

As described above, existing steel shelters, such as those shown in Fig. 2, have questionable safety because they were not made based on ballistic ejecta impact standards. Moreover, using steel plates in plate form does not make full use of steel's work-hardening potential. Accordingly, considering the damage caused by the Mt. Ontake eruption (estimated impact energy of 9 kJ for the most common, 128 mm diameter projectiles), we developed a steel shelter for this study that uses deck plates (i.e., steel with improved flexural strength provided by work-hardened trapezoidal corrugated plates). The main objective of this section was to verify the impact resistance of the deck plate material under impact from ballistic ejecta by conducting simulated ballistic ejecta impact experiments. However, it is difficult to process the deck plate of stainless steel due to its high strength (e.g. SUS304), and the processing technology has not been developed yet. Although there is a problem of corrosion resistance, SS400 was used as the material for the deck plate.

# Experimental method

## Simulated ballistic ejecta projectile

Although the range of natural density of the ballistic block is wide (e.g., Breard et al. 2014), the density of approximately 2400 kg/m<sup>3</sup> was adopted in this study. Similar to a previous study (Yamada et al. 2018), the projectiles were made from a series of 90-mm-diameter cylindrical abrasives (from white alumina used for grinding with grinding machines) to produce a simulated ballistic ejecta projectile (hereafter referred to as a projectile) with a mass of 2.66 kg (equivalent to a sphere with a diameter of 128 mm). This projectile had hardness comparable to ballistic ejecta.

Table 3 Comparison of results for steel plate (SUS304 and SS400) and aramid fabric

Material	Condition preventing impact energy of 9 kJ for ballistic ejecta	Mass per unit area (kg/m <sup>2</sup> )		
SUS304	Thickness of 1.5 mm ( $E_p = 11 \text{ kJ}$ )	11.85		
SS400	Thickness of 3.2 mm ( $E_p = 14 \text{ kJ}$ )	24.96		
Aramid fabric Toray Kevlar® fabric: FS3300	Two-ply ( $E_p = 13 \text{ kJ}$ )	Above 0.9		

# SS400 deck plate specimen

Figure 5 shows the deck plate made of SS400 (hereafter referred to as the deck plate) used in this study. In this study, galvanized SS400 was used. As previously described, for an unprocessed SS400 steel plate, a thickness of at least 2.55 mm is required to prevent damage from impact with an energy of 9 kJ. However, we used a 2.3-mm-thick plate (2.34-2.35 mm) for this experiment because the flexural strength is increased through work-hardening by changing the cross section into a trapezoidal corrugated shape. The plate was cut to dimensions of 750 mm (length) × 570 mm (width) to fit the fixing frame of the impact test equipment.

Permanent steel shelters should be integrated into the natural environment. Hence, we covered the exterior of the steel shelter with stones (pumice), sandbags, and plants to make it blend into the landscape. For the impact experiment, artificial pumice (hereafter referred to as pumice), with a composition and a specific gravity similar to those of natural pumice, in sandbags was placed in front of the specimen, as shown in Fig. 6. The





Before installation of artificial pumice (basic specimen) and (**b**) after installation of artificial pumice (pumice-containing specimen)

sandbag containing pumice is approximately 180 mm thick. The pumice used in this study was an inorganic porous material made from 96% waste glass. Its particle size was approximately 2 to 75 mm and its shape was irregular. The density in oven-dry conditions was between 300 and 600 kg/m<sup>3</sup>. The quantitative effect should be examined by evaluating the strength of the pumice. However, this study is limited to qualitative comparisons of specimens with and without pumice. Specimens without pumice are referred to as basic specimens and those with pumice are referred to as pumice-containing specimens.

### Simulated ballistic ejecta impact test

As in a previous study (Yamada et al. 2018), impact tests were carried out using a pneumatic impact test

apparatus. In the previous study, the specimen was fixed between steel frames during the impact test on a simulated roof specimen. In the present study, the deck plate specimen was fixed directly to the frame using bolts. The projectile impacted the protruding section at the center of the deck plate specimen. The state of impact was recorded from the side using a high-speed camera (nac Image Technology, MEMRECAM Q1v) at 8000 frames per second with a 640 (horizontal) × 480 (vertical) resolution.

# Experimental results and discussion Basic specimen

Items 1 to 4 in Table 4 are the results of the simulated ballistic ejecta impact tests for the basic specimen. Even for the fastest impact (No. 4, energy of approximately 13.5 kJ), the projectile did not penetrate the basic specimen. As shown in Fig. 4, withstanding an impact of about 7.5 kJ is the limit for a 2.3-mm-thick SS400 unprocessed plate. Unlike the deformation mechanism for ar-tillery shells (e.g., Corbett et al. 1996; Børvik et al. 1999) and space debris (e.g., Liou and Johnson 2006) that of volcanic ejecta, which travel slower, can be considered to be dominated primarily by bending deformation. Thus, increasing the flexural strength of the deck plate structurally has a considerable effect.

Figure 7a shows the state of deformation for specimen No. 4 after the impact test and the recovered simulated ballistic ejecta projectile. It can be seen that the projectile impacts almost straight with the central projection. A combination of buckling deformation and bending deformation appears near the impact region. This indicates that larger plastic deformation is induced around the impact region compared to that for the plate specimen. In addition, specimen No. 4 deformed plastically as a whole, which contributed to the large impact energy absorption. The projectile was severely fractured. Some of projectile fragments fell apart and could not be recovered. Figure 7b shows the state of deformation for specimen No. 1 after the impact test and the recovered simulated ballistic ejecta projectile. When the impact energy decreases compared to specimen No. 4, the deformation is mainly in the impact region and the overall deformation is smaller than that for specimen No. 4. The simulated ballistic ejecta projectile had a slightly chipped edge; it did not exhibit the large fracture shown in Fig. 7b. Therefore, the strength of the ballistic ejecta projectile affects how energy is transferred into the target. In previous studies (Yamada et al. 2018; Yamada et al. 2019), the strength of the ballistic ejecta was not examined. It should be considered in a future study. The above experimental results show that considering both the mechanical and structural properties of materials can lead to stronger and lighter shelters.

# Pumice-containing specimen

Items 5 to 9 in Table 4 are the results of the simulated ballistic ejecta impact tests for the pumice-containing specimens. Because part of the pneumatic impact test apparatus was damaged during the testing of a basic specimen (No. 4), we conducted an impact experiment at approximately 90 m/s or less for safety reasons. The results of items 5 to 9 in Table 4 show that the projectile did not penetrate the pumice-containing specimens.

An example of the state of projectile impact on the pumice and deck plate specimen taken with the highspeed camera for specimen No. 8 is shown in Fig. 8. After impacting the pumice, the projectile immediately impacted the deck plate, deformed it (see bulging at the extreme right (back of the specimen) after 0.023 s in Fig. 8), and then finally bounced away without penetrating. The video data indicate that there was no significant decrease in projectile speed even after the projectile hit the sandbag filled with pumice, which shows that the projectile was buried within the sandbag. Therefore, the impact deformation states of the basic and pumicecontaining specimens obtained at similar projectile speeds were compared. Figure 9 shows the deformation state of basic (No. 2) and pumice-containing specimens (No. 7) after the impact test. With or without pumice,

Table 4 Results of simulated ballistic ejecta impact tests on SS400 deck plate with and without pumice

No.	Type of specimen	Impact velocity (m/s)	Impact energy (kJ)	Result
1	Without pumice (Basic specimen)	64	5.4	Deformed but not penetrated
2		86	9.8	
3		90	10.6	
4		101	13.5	
5	With pumice	83	9.2	
6	(pumice-containing specimen)	84	9.4	
7		87	10.1	
8		91	11.0	
9		91	11.0	



the projectile impacted at almost normal incidence the protruding section at the center of the specimen. Although it is difficult to show a quantitative difference, clear impact marks (arrows in Fig. 9) can be seen on the basic specimen but not on the pumice-containing specimen. As shown in Fig. 10, there was hardly any loss of energy due to projectile deformation or fracture in this experiment because the projectiles after impact showed almost no chipping or damage for the pumicecontaining specimen.

In order to quantitatively evaluate the impact absorption effect of pumice, the impact test on roof-simulating structure was performed. Originally, the effect of pumice should be examined on a 2.3-mm-thick SS400, but the





impact absorption effect of that could exceed the limit of the test apparatus. Therefore, we decided to use the wooden roof-simulating structure. This structure is Japanese cedar (Tenryu, Hamamatsu, Shizuoka Prefecture, Japan) with a thickness of 15 mm as roofboard installed on the surface waterproof sheet and 0.4 mm thick Galvalume° steel sheet (55% aluminum-zinc alloy steel sheet; hereafter "Galvalume steel sheet") but also one having an additional rafter installed (for details, see Yamada, et al. (2018)). In the roof-simulating structure, it was clear that the boundary between penetrating and nonpenetrating impact energy was taken to be near 1.2 kJ (Yamada et al. 2018). Similar to the pumice-containing specimen, the sandbag containing pumice (approximately 180 mm thick) was installed on the roofsimulating structure and an impact test was conducted. Table 5 shows the results of the simulated ballistic ejecta impact tests on roof-simulating structure with pumice. Due to the installation of pumice, the boundary between penetrating and non-penetrating impact energy was taken to be near 3.7 kJ. Therefore, the impact absorption energy of pumice used in this study can be calculated as approximately 2.5 kJ. Note that this value varies greatly depending on the material type and thickness. In addition, the above result reflects the effect of the installation of pumice on the roof-simulating structure. Therefore, even if the pumice is placed on steel materials, the same impact absorption energy is not always obtained. However, since the effect was shown with the roof-simulating structure that is weaker than the steel material, there is no doubt that the impact absorption energy will be improved by the installation of pumice on the steel material.

Therefore, the effect of installing artificial pumice was confirmed. For actual shelters, pumice is useful in terms of increasing strength as well as improving appearance (i.e., making a shelter blend into the surroundings). Another noteworthy point is that pumice could prevent ejecta from fragmenting on impact (Williams et al. 2019) and thereby make people less likely to be struck by



**Table 5** Results of simulated ballistic ejecta impact tests on roof-simulating structure with pumice. For the roof-simulating structure without pumice, the boundary between penetrating and non-penetrating impact energy was taken to be near 1.2 kJ (Yamada et al. 2018)

No.	Type of specimen	Impact velocity (m/s)	Impact energy (kJ)	Result
1	Roof-simulating structure with pumice (Japanese cedar with a thickness of 15 mm)	52	3.6	Deformed but not penetrated
2		53	3.8	
3		54	3.9	Penetrated
4		55	4.0	

fragments. It can be said that the effect of reinforcements such as pumice is important for the installation of shelters at active volcanoes.

# Example of shelter using deck plates

Figure 11 shows an example of a steel shelter built using SS400 deck plates (Toko Tekko Co., Ltd.), and installed near the Otaki Chojo Sanso hut on Mt. Ontake (b). These plates are capable of preventing damage caused by an impact energy of 13.5 kJ and more. Cold forming using the bending process was performed on the SS400 deck plate to process it into an arc shape. Two of these processed plates were then assembled and connected with bolts at the top to make an arched shelter. Because the flexural rigidity of the deck plate is very high, it is possible to make a self-standing structure without structural columns. This shelter can be designed to match the characteristics of a specific volcano region such as uneven and steep terrain. By making one unit of the shelter small enough to meet transportation requirements, the shelter can be prefabricated, transported, and assembled on site. A similar shelter used at Showa Station in Antarctica has been able to withstand the polar environment, including outdoor temperatures of below - 40 °C and blizzards with maximum instantaneous wind speeds of over 60 m/s (Genshiryoku Sangyo Shimbun 2018). Hence, the shelter can be installed permanently and survive the winter, even at altitudes of 2000 to 3000

m. In this study, the material was galvanized to prevent rusting; the long-term corrosion resistance to volcanic gases was not examined. A study on durable coatings and their resistance to volcanic gases should thus be carried out. In addition, processing 2.3-mm-thick plates is the limit given the current technology. Developments in processing technology will improve the shelter.

### Conclusions

The most effective safety measures against volcanic ballistic hazards are the designation of restricted access areas. On the other hand, the damage and casualties caused by the Mt. Ontake eruption in 2014 highlighted the need for better evacuation facilities that are suitable for the target location especially in cases of unheralded phreatic eruptions. Accordingly, in this study, we proposed the use of easily available and relatively inexpensive steel materials for building shelters. Assuming that the impact energy of ballistic ejecta is 9 kJ and more, as was done in previous studies, we first considered a method for reinforcing wooden buildings using SUS304 and SS400 unprocessed steel plates to withstand impacts with this energy. Without using previously proposed aramid fabric, we focused on workability and material price and demonstrated that it is possible to reinforce mountain huts relatively inexpensively by using SUS304.

SUS304 is suitable for use as a reinforcing material because it has excellent impact energy absorption due to





its high ductility, as well as excellent corrosion resistance. However, the construction cost with light aramid fabrics is lower than that with SUS304 in high-altitude mountain huts. It is thus necessary to take the transportation and construction cost of materials into account. The material and construction method should be suitable for the target environment. If there are no restrictions on the construction requirements and cost, RC shelters provide the best impact resistance to ballistic ejecta. Nevertheless, the results of this study can be used to select a reinforcement method that best matches location restrictions.

To increase the structural strength of steel shelters, we also conducted an impact experiment on a shelter using galvanized SS400 deck plates loaded with pumice. The results showed that the shelter could withstand impact with an energy of 13.5 kJ and more. Because there is still some allowance for deformation caused by projectile impact, this steel shelter holds promise, not only structurally, but also from the aspects of transportation and assembly.

In future studies, it will be necessary to consider how the corrosion resistance and mechanical properties of SUS304 and galvanized SS400 can be maximized in environments exposed to corrosive volcanic gases. By aiming for the construction of maintenance-free evacuation facilities and shelters with good corrosion resistance, we hope to help reduce the installation and maintenance costs associated with ballistic ejecta shelters.

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#### Authors' contributions

HY planned the research and prepared the manuscript. KT summarized the entire impcat test using a pneumatic impact test apparatus. SN and HS conducted a survey on the current status of shelters in Japan and assisted in the impact tests. ST prepared deck plate specimens and conducted the impact tests. RH, TK, MY and TF performed the impact tests. The authors read and approved the final manuscript.

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#### Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

#### Declarations

#### **Competing interests**

The authors declare that they have no competing interests.

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