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Research Article

Study on Construction and Optimization of the Life-Saving Passage in Building Ruins Based on Numerical Simulation Method

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It is a very important task to construct a life-saving passage in building ruins rapidly and scientifically in the process of earthquake rescue. Currently, the virtual scene is built to train rescuers to construct the life-saving passage quickly and scientifically. However, there are problems such as high cost, small quantity, and single form. A new method of constructing building ruins and life-saving passage was proposed based on the combined finite element (FE) and finite-discrete element (F-DE) method and restarted function of LS-DYNA program. First, taking the RC frame structure ruins as research objection, the different types of life-saving passages were constructed. What's more, a simple and reasonable optimization method of life-saving passage is proposed based on the rescue technologies with the shortest time. Meanwhile, the timing test of four typical rescue technologies was performed considering the influence factors of various rescue situations. Finally, the practicability and validation of the optimization method was verified through comparing with actual earthquake rescue case. The results show that the restart function of ANSYS/LS-DYNA program can construct the life-saving passage rapidly and reasonably, and simultaneously, the optimal method of life-saving passage can give the optimal rescue route intuitively and accurately. The numerical simulation method of construction and optimization of life-saving passages is expected to provide theoretical guidance for rescue drills for on-site earthquake rescue.

1. Introduction

Effective and rapid earthquake emergency rescue has proved to be the key measure and available behavior of disaster reduction in many earthquakes [1, 2]. We can reduce the casualties caused by earthquake disasters as much as possible when the importance of earthquake emergency rescue is fully recognized and the rescue ability is improved [3, 4]. It is a very important task for earthquake emergency rescue to construct the life-saving passage safely and rapidly in the building ruins [5–7]. The life-saving passage is a safe passage for rescuers to enter and save trapped people to evacuate the stacking ruins or manually using corresponding rescue technologies according to《INSARAG International Search and Rescue Guide》[8]. Multiple life-saving passages can be constructed in the same building ruins, and simultaneously, the reasonable selection of the life-saving passage can play a key role in ensuring the "double safety" of rescuers and trapped people based on the earthquake rescue cases [9–11]. Therefore, it is great significance to study the method of quickly constructing and optimizing life-saving passage in building ruins for the actual earthquake rescue and training drills. However, the construction and optimization of life-saving passages in building ruins are currently based on the technology or experience at home and abroad, for example, FEMA's various rescue procedures [12], rescue standards [13], Europe's saver rescue technology [14], and the United Nations' five steps of rescue [8], which are generally lack of corresponding theoretical research.

Virtual scenes of building ruins have been built at home and abroad to improve the rescue ability to enhance rescue experience of rescue teams, among which, the construction of the life-saving passage is the main task of rescue training. Miami Emergency Rescue Center of the United States spent 400 million dollars to build a simulation training building ruins [15]. The Russian "179" training base set up a scene of building ruins of urban search and rescue training with a total investment of $15. In 1999, a simulation training scene of earthquake ruins was built in the Singapore Civil Defense Academy of Civil Buildings [16]. In 2000, four typical building ruins were built in USAR training center in China, such as, pancake-type building ruins, incline-type building ruins, small space-type building ruins and V-type building ruins [17], as shown in Figures 1(a)–1(d). However, the above-mentioned building ruins have many problems, such as high cost, small quantity, single form, which leads to the ineffective and adequate implementation of training drills for the construction of life-saving passage. Presently, researchers both domestically and internationally have already tried to use virtual simulation methods to build virtual scenes of building ruins to remedy the above-mentioned problems. The Human Computer Interaction Laboratory of University of Udine in Italy used virtual modeling technology to construct the three-dimensional building ruins of a magnitude 6.4 earthquake in Friuli, Italy, on May 6, 1976 [18]. The University of Tokyo used the discrete element method and graphic technology to build the seismic ruins model of RC frame structure [19]. Gu Xianglin and Sun Feifei, from Tongji University, can convert the digital information of numerical simulation into graphical static or dynamic screen display through graphic technology, which can build the simulation model of building ruins quickly [20]. Wu Weihuang, from Tsinghua University, proposed a multimedia simulation system to construct a building ruins model based on graphic processing [21]. Wang Dongming, from the Institute of Engineering Mechanics of China Earthquake Administration, used computer simulation technology to realize the building model of earthquake disaster scenes [22]. The above researchers can realize the construction of building ruins to a certain extent based on the virtual simulation method. However, most of the building ruins are macrosimulation models, which cannot truly reflect the mechanical characteristics of building ruins. Similarly, the subsequent construction methods of the life-saving passages in building ruins are rarely investigated.

Currently, there are many numerical simulation investigations on building collapse ruins based on structural dynamics theory; for example, finite element method (FEM) [23], discrete element method (DEM) [24], and applied element method (AEM) [25] were realized RC frame structure collapse ruins. However, most scholars pay little attention to the collapse mode, including the survival space and life-saving passage. The collapse numerical simulation of three-dimensional structure with infilled walls is of great significance to the construction of building ruins and life-saving passages. In 2020, Zhao [4] used finite element method and physics engine to realize the seismic collapse of three-dimensional building collapse simulation with infilled walls; however, it is not easy to realize the subsequent construction of life-saving passage. In 2021, Author Xu et al. utilized ANSYS/LS-DYNA program to simulate the seismic collapse of three-dimensional RC frame structural with infilled walls based on the combination of FE and F-DE method [26, 27]. The restart function of ANSYS/LS-DYNA program provided the restart function that can realize subsequent calculation on the premise of retaining the previous stress state [28, 29]. Therefore, this paper attempts to utilize ANSYS/LS-DYNA program to construct the numerical simulation of life-saving passage after the building collapsed.

As an important task in rescue, the optimization of life-saving passage has given some suggestions. For example, 《Earthquake Search and Rescue Manual》 and 《Earthquake Safety Manual》 published by the Federal Emergency Management Agency (FEMA) of the United States, which proposed the methods and procedures of earthquake disaster rescue, the basic principles of building rescue optimization method, building rescue sequencing, and the ten steps method of building rescue. However, most of the existing specifications are based on experience and lack of relevant theoretical support. The rapid construction of saving-life passage in building ruins is realized based on the numerical simulation method in this paper. Simultaneously, the optimal method of saving-life passage is proposed based on the premise of ensuring the "double safety" of rescuers and trapped people and the goal of rescuing the most trapped people in the shortest time. It provides scientific and reliable basis for the earthquake site commanders to determine the rescue direction quickly and the life-saving passage safely.

Subsequently, the method of constructing the life-saving passage in collapsed building is numerically simulated and described in Section 2. The horizontal and vertical life-saving passages are constructed using RC frame structure as the research object in Section 3. In Section 4, the timing test of rescue technology is performed, the optimal method of the life-saving passage is proposed, and the construction of the life-saving passage in Chapter 3 is optimized. In Section 5, the practicability and validation of the optimization method were verified through comparing with actual earthquake rescue case. The framework is added to explain the content of this paper clearly, and similarly, the actual earthquake rescue case is added to verify the accuracy and rationality of results, as shown in Figure 2.

2. Numerical Simulation Method of Construction of Lifesaving Passages

The four basic rescue technologies for constructing life-saving passages in building ruins include the removal rescue technology, the shoring rescue technology, the uplift rescue technology, and the breach rescue technology according to 《INSARAG International Search and Rescue

(a)

(b)

(c)

(d)

Figure 1: Typical type building ruins in USAR training center in China (Source: Zhang Jianqiang): (a) pancake-type building ruins, (b) incline-type building ruins, (c) small space-type building ruins, and (d) V-type building ruins.

Guide》 [8], 《Operation for earthquake search and rescue team-Part 1: Basic requirements of operation》 [30], and《Operation for earthquake search and rescue team-—Part 2: Procedures and methods》 [31], as shown in Figures 3(a)–3(d). Among them, the removal rescue technology means that the rubble at the edge of the ruins, and unstable small components can be removed, and the beam and column plates can be lifted to construct saving-life passage in rescue process; the shoring rescue technology can ensure the safety of the constructed saving-life passage for the temporary shoring of unstable space during rescue process; the uplift rescue technology means that collapsed structures with good integrity can be lifted to construct horizontal or vertical saving-life passage in rescue process; the breach rescue technology refers to various operations such as stripping, splitting, and chiseling of structural components to construct the saving-life passage during rescue process. Four basic rescue technologies can be flexibly used and reasonably combined according to the operating capacity of the confined space, equipment stability, and the spacious size of the saving-life passage. Therefore, it is necessary to “re-edit” the structural components elements of the numerical model to realize the above-mentioned rescue technologies of constructing the life-saving. The structural components of numerical models of building ruins are deleted, added, and loaded to realize removal or breach, shoring, and breach technology. The ANSYS/LS-DYNA program was used to simulate the seismic collapse of building structures. The combined finite element (FE) and finite-discrete element (F-DE) method is used to simulate three-dimensional RC frame structure with infilled wall. Then, the D3DUMP file is generated to construct the life-saving passage of RC frame structure ruins, as shown in Figure 4.

The restart calculation function of LS–DYNA program can be utilized in continuous calculation and analysis in multiple fields, such as car crash, building blasting collapse, and repeatedly loaded mechanical equipment. Bao and Hu used the restart function of LS–DYNA program to realize the frontal crash simulation of the whole vehicle without restraint system [32]. Zhang applied the restart function of LS–DYNA program to simulate the blasting collapse of thin wall tubular structures. First, some structural elements were deleted to be equivalent to the demolition blasting of thin wall tubular. Then, the thin wall tubular structures collapsed under the gravity load [33]. Liu et al. developed the finite element (FE) model of the shallow buried tunnel arch under the internal explosion by adopting the arbitrary Lagrangian–Eulerian (ALE) algorithm in LS–DYNA. The full restart function of LS–DYNA program was further employed to calculate the bearing capacity of the specimens [34]. Dong simulated a new type forklift overhead guard based on LS–DYNA. The restart function was applied to accomplish repeated loading on the premise of retaining the previous stress state [35]. Deng analyzed the dynamic pile sinking process based on LS–DYNA. The multiple hammer loading of pile sinking was realized by using the restart function of LS-DYNA program [36]. Lin and Qu analyzed the cumulative damage of vehicle battery pack under repeated impact loads. The cumulative analysis of stress and plastic strain of the structure under repeated impact load can be obtained by using the restarting technique of LS–DYNA program [37].

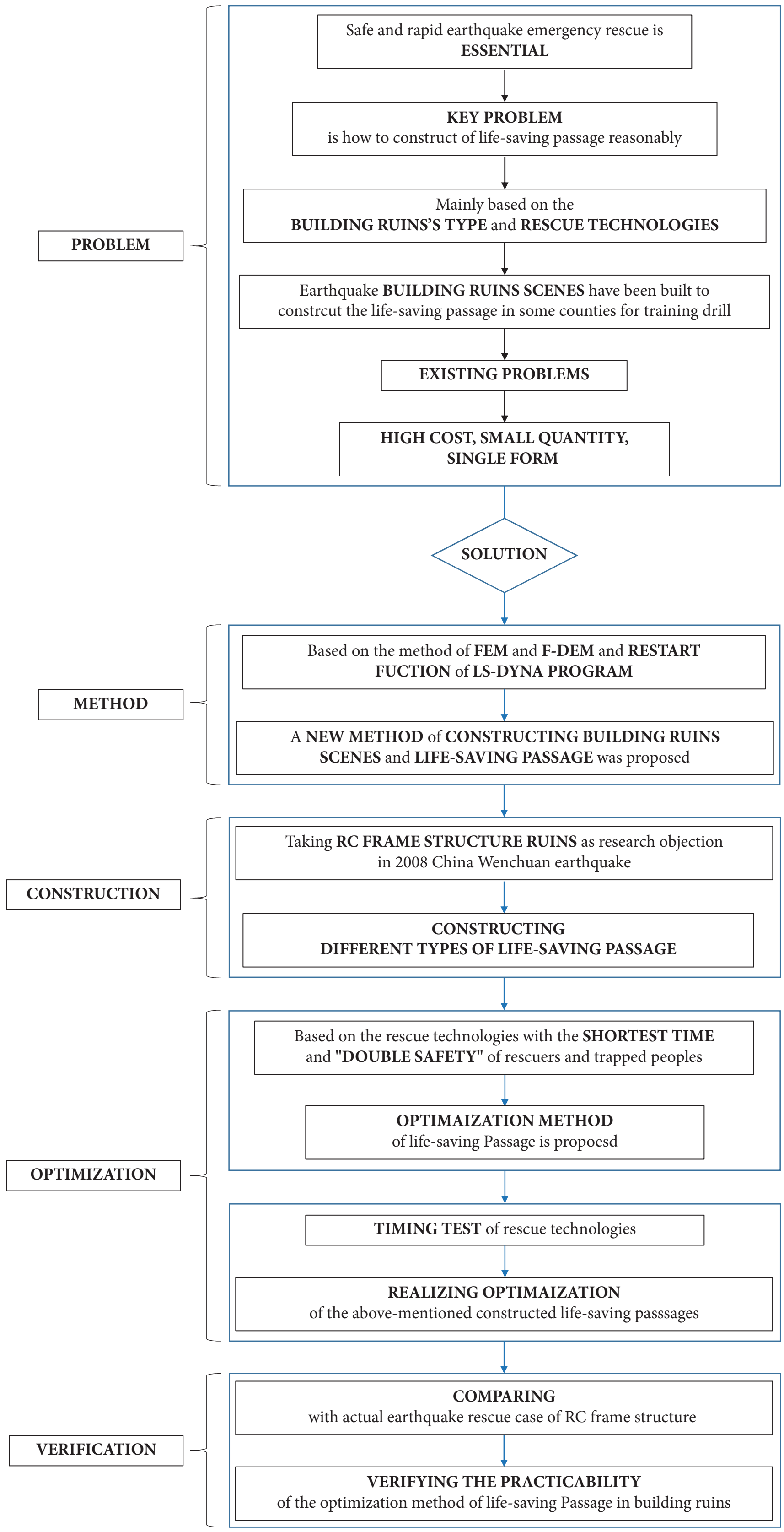

Figure 2: The research content flowchart of this paper.

FIGURE 3: Basic rescue technologies (source: Zhang Jianqiang): (a) removal rescue technology, (b) shoring rescue technology, (c) uplift rescue technology, and (d) breach rescue technology.

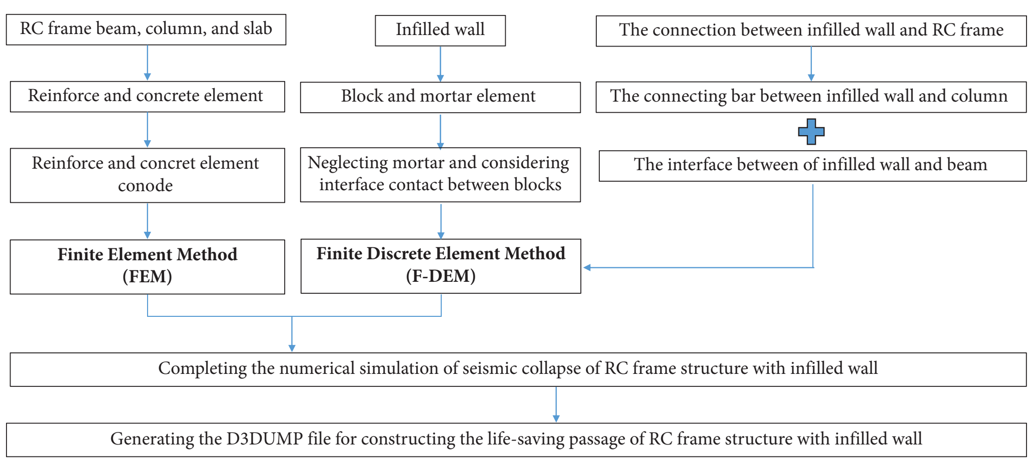

FIGURE 4: The numerical simulation method of collapse ruins of RC frame structure.

To sum up, the restart function of LS-DYNA program is utilized to re-edit the numerical model to finish the above-mentioned research aims. The elements of numerical model are deleted, added, and loaded repeated on the premise of retaining the stress and strain of previous numerical model. Therefore, this paper attempts to utilize the restart function of LS-DYNA program to construct the life-saving passage through re-editing numerical simulation of building ruins. The numerical model elements of building ruins are deleted, added, and loaded repeatedly to realize removal or breach, shoring, and breach technology, which are essential means to construct a life-saving passage in the building ruins. The calculation flowchart of the restart technology of the ANSYS/LS-DYNA program is shown in Figure 5. The key step of the restart technology is that it can modify keywords (K) file 1 to new K file $1 + i$ ($i = 1, 2, 3, \ldots$) after solving the problem. Then, the elements of numerical model are deleted and added based on retaining the stress and strain of the ruin's numerical model. Keywords are shown in Table 1.

3. Construction of the Life-Saving Passages of RC Frame Structure Ruins

Taking the numerical model of RC frame structure ruins as an example, as shown in Figure 6, the horizontal and vertical life-saving passages are constructed according to the distribution characteristics of survival spaces and the application characteristics of rescue technologies. There are three

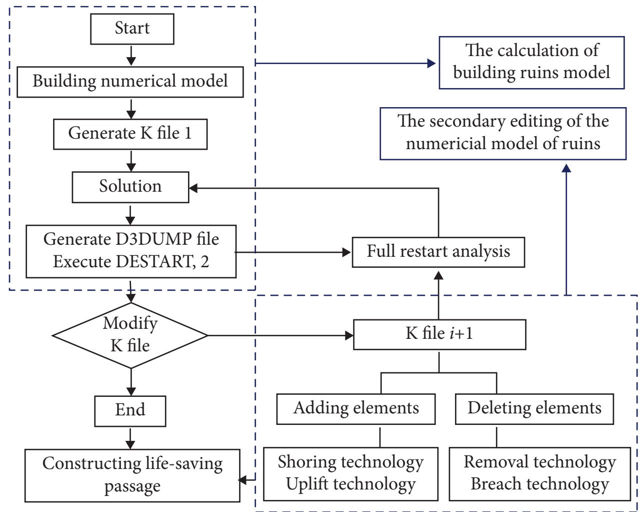

FIGURE 5: The restart technology of the ANSYS/LS-DYNA program.

TABLE 1: Full restart keywords of ANSYS/LS-DYNA [28].

Function	Keywords	Model
Retaining stress and strain of numerical models of the ruins	∗ STRESS_INITIALIZATION	Whole numerical model of the ruins
Adding shoring elements in the numerical model of the ruins	∗ ADD_ELEMENT	The shoring element model
Deleting removal and breach elements in the numerical model	∗ DELETE_ELEMENT	Ruins elements model
Inputting time history curve of aftershock acceleration	∗ CHANGE_CURVE_DEFINITION	Whole numerical model of the ruins
Extending the calculation time of the modified numerical model	∗ CONTROL_TERMINATION	Whole numerical model of the ruins
Resetting the interval or frequency of the output file	∗ CONTROL_BINARY_OPTION	Whole numerical model of the ruins

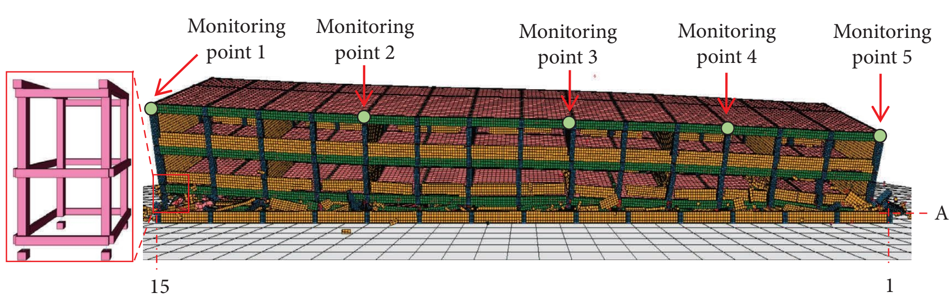

FIGURE 6: The numerical model of RC frame structure ruins.

combinations of rescue technologies according to the experiences of earthquake site rescue [38–40]. The combinations are as follows: (I) the breach technology/shoring technology⟶the removal technology⟶the breach technology⟶the removal technology; (II) the removal technology⟶the shoring technology⟶the removal technology; (III) the breach technology⟶the removal technology⟶the breach technology⟶the removal technology. The two upper floors of RC frame structure ruins have not been damaged; thus, the combination III is not considered. The vertical and horizontal life-saving passage of combination I and II are shown in Figures 7 and 8.

In Figures 7 and 8, combination I and II give 5–6 steps in the rescue route, which include rescue technologies, wounded treatment and victim transportation. It is necessary to evaluate the safety of RC frame structure ruins to construct the life-saving passage. Thus, the ruins are prone to secondary collapse should be shored at the intersection of the frame column at the intersection of the Axis A and 1 is seriously damaged. The calculation formula for selecting the wood shoring is given according to the bearing condition of the frame column, as shown in formulas (1) and (2). F_d value for the bearing capacity of different types and sizes of wood shoring can be determined according to《DHS Field Guide

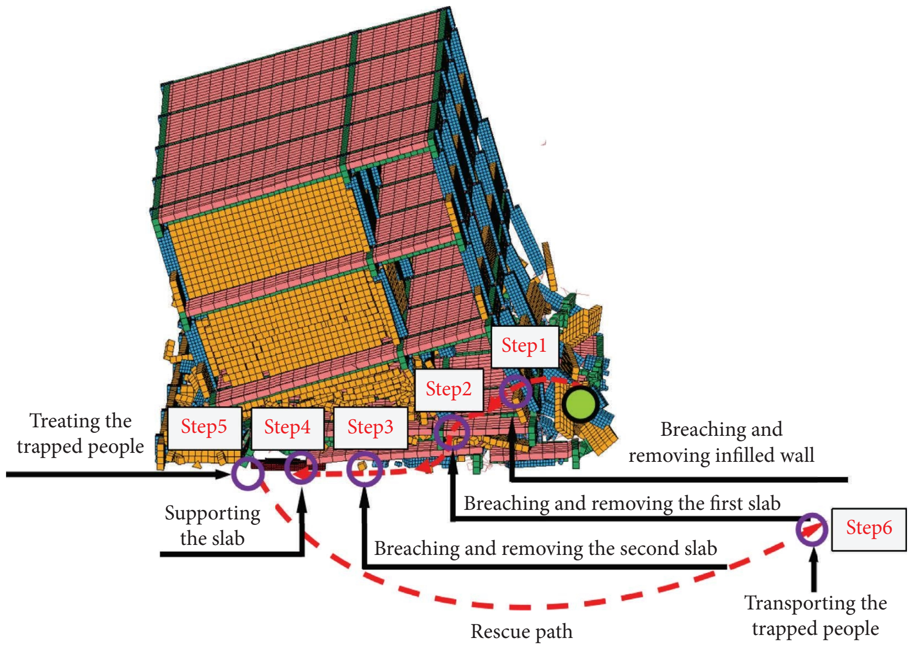

Figure 7: The vertical life-saving passage of RC frame structure ruins.

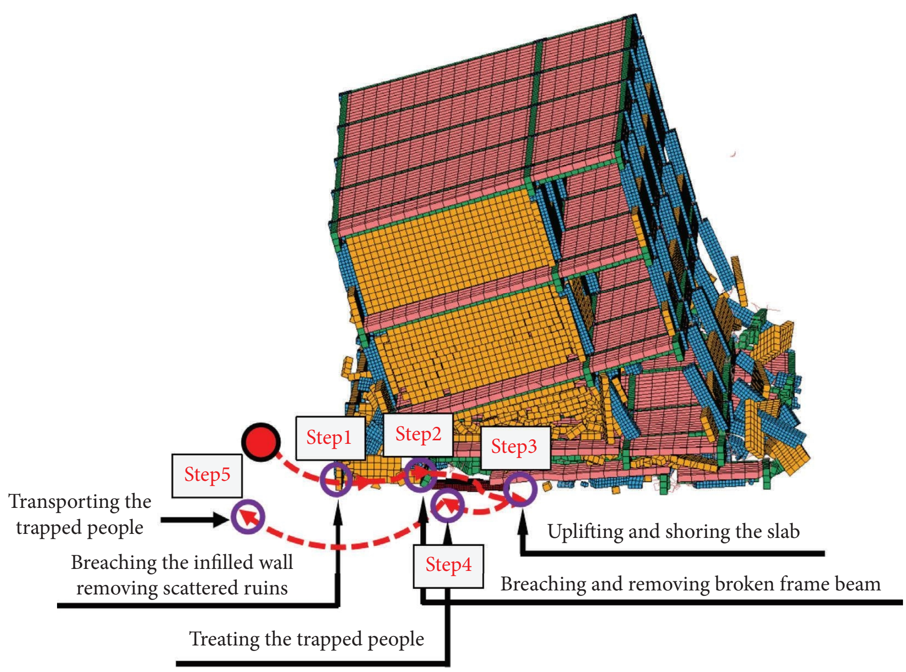

Figure 8: The vertical life-saving passage of RC frame structure ruins.

for Building Stabilization and Shoring Technologies》 [41]. P value is gained according to 《the Operation Guide for Urban Search and Rescue and Rescue shoring》compiled by Chen [42]. R value is obtained according to 《Criteria and criteria for damage assessment of reinforced concrete and steel reinforced concrete buildings》 [43]. According to formula (2), F is equal to 132 kN. Three-dimensional wood shoring with column height of 1600 mm is selected. The design value of bearing capacity of wood shoring bearing capacity is 159 kN according to the specification [44], that is, $F \leq F_d$, which meets the following requirements:

$$F \leq F_d, \tag{1}$$

$$F = N \times S \times P \times (1 - R), \tag{2}$$

where F is the bearing load of wood shoring, F_d is the design value of bearing load of wood shoring, S is the bearing area of

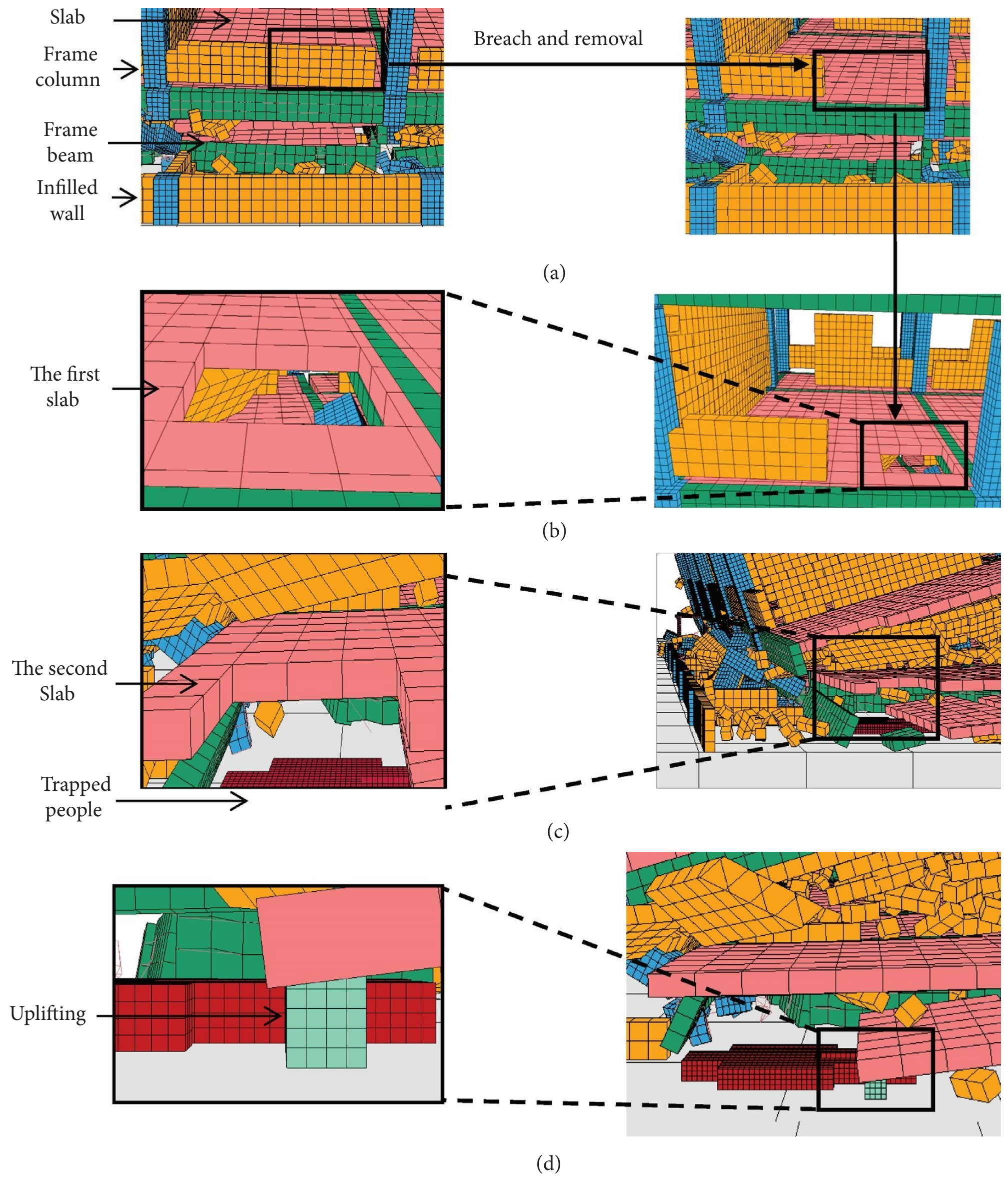

FIGURE 9: (a) Breaching and removing the infilled wall elements, (b) breaching and removing the first slab elements, (c) breaching and removing the second slab elements, and (d) uplifting and shoring the slab.

wood shoring, N is the number of floors, P is the design static load of building materials, and R is the residual bearing rate of the RC frame column.

3.1. Construction of Vertical Life-Saving Passage. The numerical model of RC frame structure ruins is re-edited, and the life-saving passage is divided into 6 key steps according to Figure 7, step 1: "∗DELETE_ ELEMENT" keywords are added to breach and remove the infilled wall elements at the entrance of the life-saving passage, as shown in Figure 9(a); step 2: "∗DELETE_ELEMENT" keywords are added to breach and remove the first slab elements, as shown in Figure 9(b); step 3: "∗DELETE_ELEMENT" keywords are added to breach and remove the second slab elements, as shown in Figure 9(c); step 4: "∗ADD_ELEMENT" keywords are added to support the slab if the leg of the trapped people is squeezed by the upper slab as shown in Figure 9(d); step 5 and step 6: the trapped people are treated and transported as shown in Figure 10.

The vertical displacement of the steps 1–4 is monitored in the process of the construction of the life-saving passage. Five monitoring points of the numerical model of collapsed RC frame structure are selected as shown in Figure 6, and the vertical displacement time history of monitoring points during the construction of life-saving passage is shown in Figure 11. It was found that the vertical displacement change of the monitoring point is small. The main reason is the nonlinear ruins state of the materials of the numerical model, which will subsequently produce vertical deformation under gravity load.

3.2. Construction of Horizontal Life-Saving Passage. The numerical model of RC frame structure ruins is re-edited, and the life-saving passage is divided into 5 key steps according to Figure 8, and step 1: " ∗ DELETE_ELEMENT" keywords are

Figure 10: Treating and transporting the trapped people.

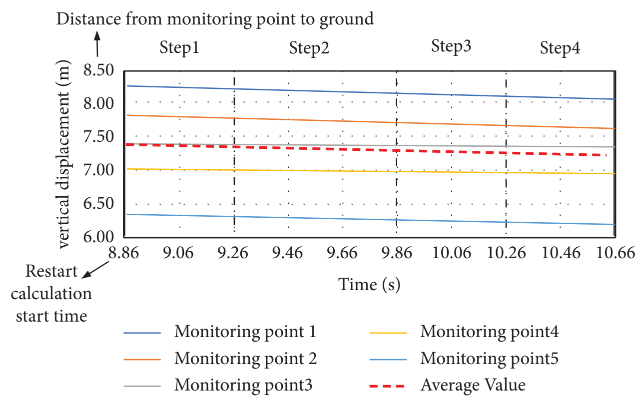

Figure 11: Vertical displacement time history of monitoring points during the construction of life-saving passage.

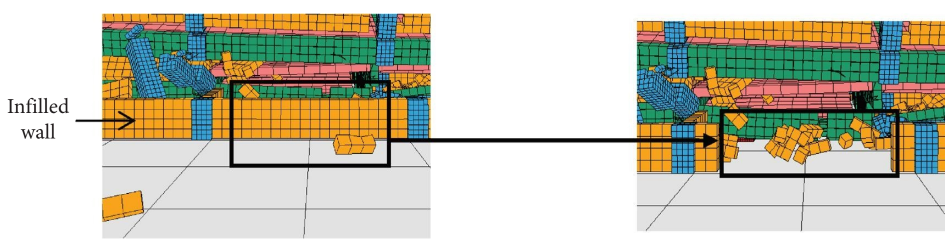

Figure 12: Breaching the infilled wall elements and removing scattered ruins elements.

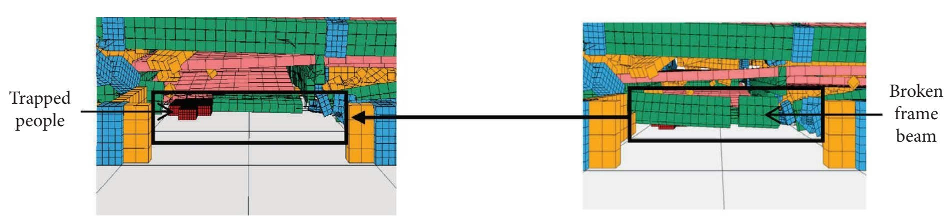

Figure 13: Breaching and removing broken frame beam elements.

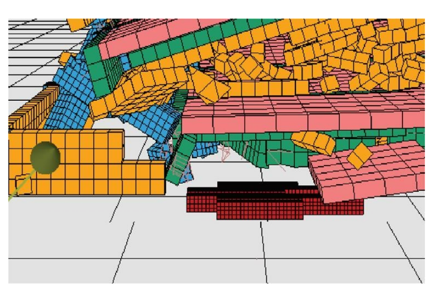

Figure 14: Relationship between the trapped and surrounding ruins.

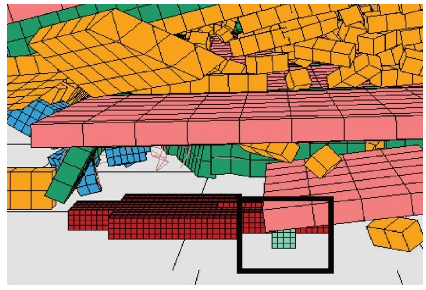

Figure 15: Uplifting and shoring the slab.

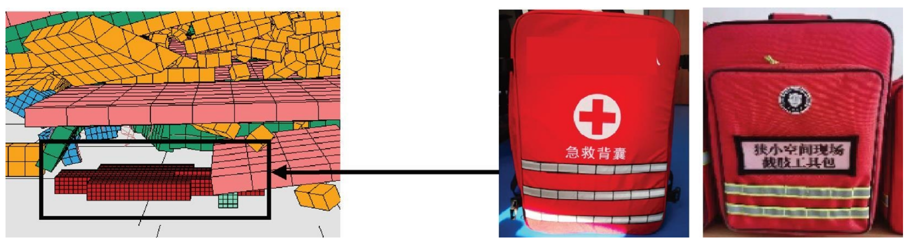

Figure 16: Treating and transporting the trapped people.

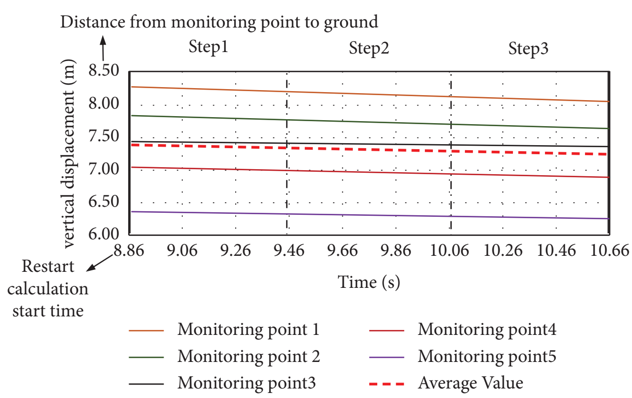

Figure 17: Vertical displacement time history of monitoring points during the construction of life-saving passage.

added to breach the infilled wall elements and remove scattered ruins elements on the ground, as shown in Figure 12; step 2: " ∗ DELETE_ELEMENT" keywords are added to breach and remove broken frame beam elements, as shown in Figure 13; step 3: " ∗ ADD_ELEMENT" keywords are added to support the slab if the leg of the trapped people is squeezed by the upper slab as shown in Figure 14; step 4 and step5: the trapped people are treated and transported as shown in Figures 15 and 16. The horizontal displacement of the monitoring points of the structural ruins was monitored during the construction of the horizontal life-saving passage, as shown in Figure 17. It was found that the vertical displacement change of the monitoring point is small.

4. Optimization Method of Life-Saving Passages

4.1. Calculation Formula for Optimization of Life-Saving Passages. It is particularly important to choose reasonable rescue technology to construct the life-saving passage of the building ruins based on the time efficiency. The principle of the combination of rescue technologies with the shortest time is taken as the optimal route of the life-saving passage based on the premise of "double safety" of rescuers and trapped people. First of all, the rescue time of different combinations of rescue technologies is calculated. Among them, the time of each rescue technology is obtained from the rescue technology timing test. Then, the shortest time T of combination of rescue technologies is taken as the optimal route, as shown in Figure 18.

The shortest rescue time T_{total} is calculated according to different types of rescue technology combinations, as shown in the following equation:

$$\mathrm{T}_{\text{total}} = \mathrm{Min}\left\{\sum_{i=1}^{6}\sum_{j=1}^{n}\mathrm{T}_{ij}\right\}, \tag{3}$$

where i is different rescue technology, and j is the number of each rescue technology.

4.2. Timing Test of Rescue Technologies. It is necessary to determine the time required for different types of rescue technologies, treating and transporting the wounded. Therefore, the research group and USAR training center have completed the timing test of rescue technologies in 2020–2022, as shown in Figures 19(a)–19(d). Timing tests of removal rescue technology take into account the weight of ruins, equipment type, traction distance, and other factors. Each group of timing tests of removal recuse technology takes the average of three tests. The test results are shown in Table 2. Timing tests of shoring rescue technology consider the manufacturing equipment, shoring type, shoring height, and other factors [45]. Each group of timing tests of shoring recuse technology takes the average of three tests. The test

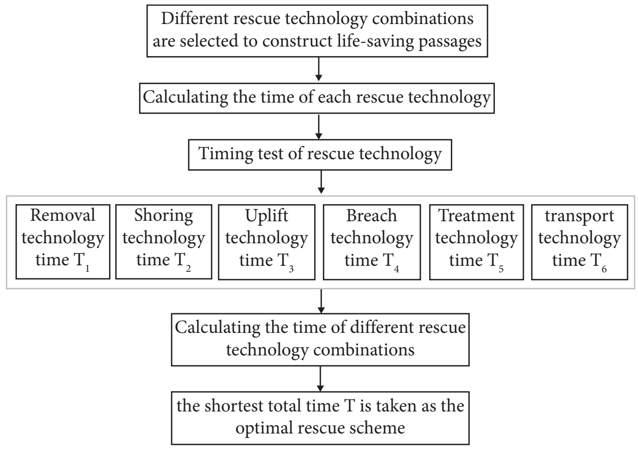

FIGURE 18: Optimization scheme of life-saving passage.

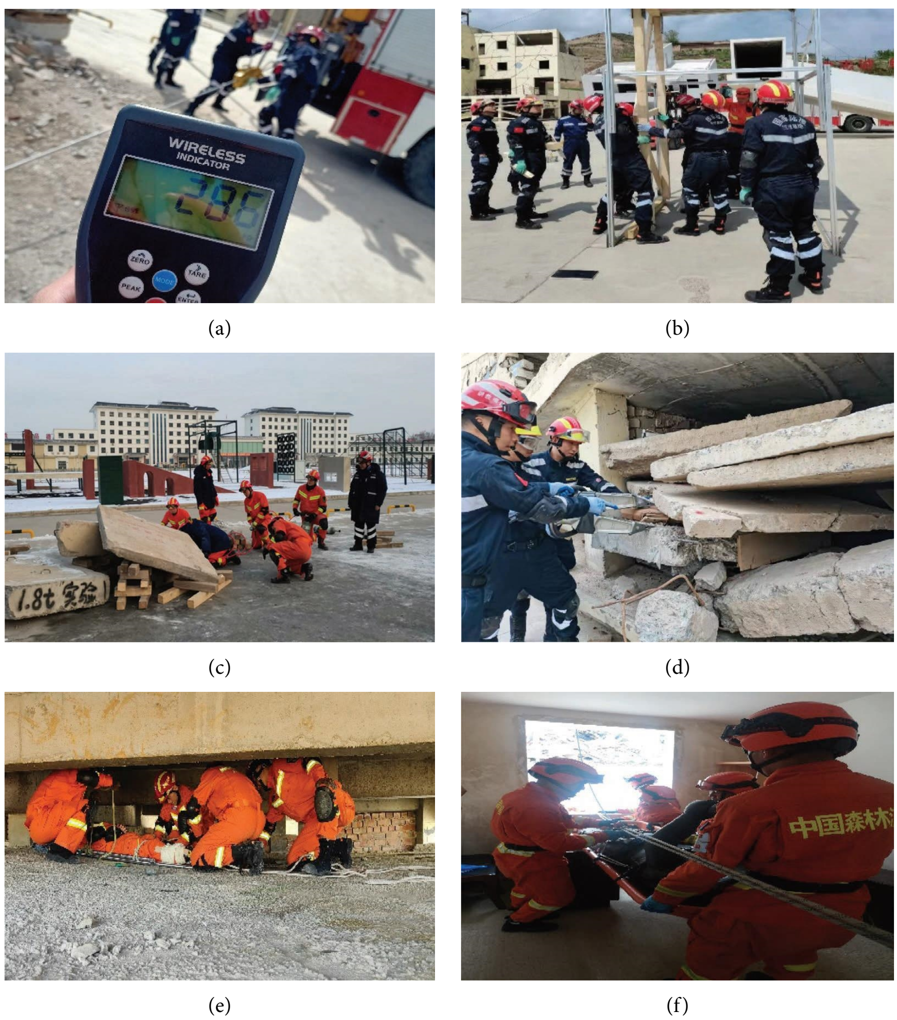

FIGURE 19: Timing test of rescue technologies (Site: USAR training center, 2020–2022): (a) timing tests of removal rescue technology, (b) timing tests of shoring rescue technology, (c) timing tests of uplift rescue technology, (d) timing tests of breach recuse technology, (e) timing tests of treating the wound, and (f) timing tests of transporting trapped people.

results are shown in Table 3. Timing test of breach recuse technology takes into account the equipment type, breach object, breach direction, breach type, and other factors. The number of breach testers in each group is about 3 according to《INSARAG International Search and Rescue Guide》[8]. The thickness of reinforced concrete floor is about 120 mm.

Table 2: Timing test of removal rescue technology.

No	Equipment type	The weight of ruins	Removing direction	Moving distance (m)	Average traction of tester (kN)	Pavement type	Average time (T)
1	Manual hoist	300 kg reinforced concrete slab	Horizontal moving	3	5	Sand pavement	18′06″
2				5		Sand pavement	22′11″
3				7		Sand pavement	40′23″
4				3		Soil pavement	23′08″
5				5		Soil pavement	29′36″
6				7		Soil pavement	49′44″
7		500 kg reinforced concrete slab	Horizontal moving	3	5	Sand pavement	37′12″
8				5		Sand pavement	46′47″
9				7		Sand pavement	67′15″
10				3		Soil pavement	33′06″
11				5		Soil pavement	43′12″
12				7		Soil pavement	64′08″
13		300 kg reinforced concrete slab	Vertical moving	3	5	—	13′17″
14				6		—	17′23″
15				9		—	30′29″
16				12		—	50′33″
17		500 kg reinforced concrete slab	Vertical moving	3	5	—	32′46″
18				6		—	49′41″
19				9		—	67′09″
20				12		—	89′56″

Table 3: Timing test of shoring rescue technology.

No	Equipment type	Shoring type	Shoring height (mm)	Number of testers	Proficiency	Average time T
1	Drama, claw hammer, handsaw, and consumables	Door and window wood shoring	1800	4	Skilled	28′32″
2					Unskilled	40′11″
3			2400		Skilled	31′16″
4					Unskilled	52′36″
5			3600		Skilled	44′48″
6					Unskilled	60′37″
7		Double column wood shoring	1800	4	Skilled	60′55″
8					Unskilled	81′23″
9			2400		Skilled	73′07″
10					Unskilled	94′03″
11			3600		Skilled	88′34″
12					Unskilled	102′16″
13		L-type wood shoring	1800	4	Skilled	66′30″
14					Unskilled	96′31″
15			2400		Skilled	67′22″
16					Unskilled	99′58″
17		3D wood shoring	1800	4	Skilled	155′44″
18					Unskilled	189′02″
19			2400		Skilled	160′19″
20					Unskilled	199′32″
21			3600		Skilled	187′08″
22					Unskilled	220′51″

Table 4: Timing test of uplift rescue technology.

No	Equipment type	The weight of uplift (t)	Uplift height (mm)	Number of testers	Proficiency	Average time (T)
1	Air cushion	1.5	600	4	Skilled	33′27″
2					Unskilled	41′02″
3			800		Skilled	57′11″
4					Unskilled	66′08″
5			1000		Skilled	72′21″
6					Unskilled	79′36″
7		3	600	4	Skilled	50′49″
8					Unskilled	63′44″
9			800		Skilled	70′32″
10					Unskilled	82′14″
11			1000		Skilled	92′16″
12					Unskilled	101′58″
13		6	600	4	Skilled	87′30″
14					Unskilled	102′43″
15			800		Skilled	110′27″
16					Unskilled	123′40″
17			1000		Skilled	144′33″
18					Unskilled	161′28″

Each group of timing tests of breach recuse technology takes into account. The test results are shown in Table 4. Timing tests of breach rescue technology take into account the equipment type, breach weight, breach height, and other factors. Each group of timing tests of breach recuse technology takes the average of three tests. The test results are shown in Table 5. The treating time is mainly related to the injury situation and the doctors' emergency handling capacity. The time for treating the wounded is 30–50 minutes according to the statistics of previous rescue experience and timing tests. The time for rescuers of transporting trapped people takes 40 minutes.

Table 2 gives the removal time of building ruins with different weights, different removal distances, and different removal paths. The rescue time is obtained in the form of interpolation according to the transportation distance in the actual rescue process. Table 3 gives the removal time of building ruins with different types and heights of wood shoring. The rescue time is obtained in the form of interpolation according to the shoring height in the actual rescue process. Table 4 gives the removal time of building ruins with different weights and uplift heights. The rescue time is obtained in the form of interpolation according to the uplift height in the actual rescue process. Table 5 gives the breach time of different floor thicknesses. The rescuers can take the value directly because the thickness of floor and wall in the test is from the actual project. The environment of training exercise has less impact on the psychological pressure of the testers of rescue technology timing test compared with the actual earthquake rescue. Aftershocks often occur at the process of earthquake rescue site, which will aggravate the psychological pressure of rescuers and affect the physical strength, especially, rescuers who have not undergone strict psychological quality training. Actually, not all rescuers have received psychological quality training at the earthquake site. So, the rescue time measured in the test is less than the actual rescue in Tables 2–5. According to Shackell et al.'s research [46], it was tested whether mental training alone can produce a gain in muscular strength. The results showed that physical strength was increased by 24% through mental practice. Therefore, an improvement coefficient of rescue technology timing test is given as 1.24, as shown in the following formula:

$$\mathrm{T}_1 = k\,\mathrm{T}, \tag{4}$$

where T_1 is the rescue time considering the psychological tension of rescuers, k is improvement coefficient, and T is rescue time in Tables 2–5.

4.3. Optimization of Life-Saving Passages. The rescue time of the horizontal and vertical life-saving passages of RC frame structure ruins is calculated according to the calculation formula of the rescue technology. The time required for constructing horizontal and vertical life-saving passages is calculated according to timing test of rescue technologies and the proficiency of rescuers, as shown in Tables 6 and 7. The optimal rescue time is calculated under the unskilled conditions according to Table 6, $\mathrm{T}_{\text{total}} = k\,\mathrm{Min}\left\{\Sigma_{i=1}^{6}\Sigma_{j=1}^{n}\right\} = 649'56$“. The optimal rescue time is calculated under the skilled conditions according to Table 7, $\mathrm{T}_{\text{total}} = k\,\mathrm{Min}\left\{\Sigma_{i=1}^{6}\Sigma_{j=1}^{n}\right\} = 559'30$“.

Table 6 shows that the construction of horizontal life-saving passage is superior to the vertical life-saving passage in the RC frame structure ruins. The main reason is that RC frame structure is prone to form pancake-type ruins under the earthquake [47–49]. The vertical life-saving passage is usually constructed to use the layered rescue method during the rescue process, and the slab needs to made holes with the breach technology. The slab breach time is longer than other rescue technologies according to the timing test of rescue technology. The rescue efficiency can be greatly improved when the rescuers master the skilled rescue techniques according to Tables 6 and 7. Thus, the rescue training is great

Table 5: Timing test of breach rescue technology.

No	Equipment type	Breach object	Breach direction	Size of breach hole	Number of testers	Breach type	Proficiency	Average time (T)
1	Electric, internal combustion, and cutting machine	Single floor, 120 mm thick reinforced concrete floor slab, double row reinforcement, longitudinal reinforcement diameter 16 mm, stirrup diameter 8 mm	Vertical breach	1.2 m in diameter	3	Safe breach	Skilled	81′33″
2							Unskilled	126′50″
3						Quick breach	Skilled	64′41″
4							Unskilled	87′46″
5		Double floor, 120 mm + 120 mm thick reinforced concrete floor slab, double row reinforcement, longitudinal reinforcement diameter 16 mm, stirrup diameter 8 mm	Vertical breach	1.2 m in diameter	3	Safe breach	Skilled	185′22″
6							Unskilled	282′43″
7						Quick breach	Skilled	148′55″
8							Unskilled	203′38″
9		120 mm thick masonry wall	Horizontal breach	1.2 m in diameter	3	Safe breach	Skilled	45′05″
10							Unskilled	55′17″
11						Quick breach	Skilled	33′24″
12							Unskilled	46′22″
13		240 mm thick masonry wall	Horizontal breach	1.2 m in diameter	3	Safe breach	Skilled	60′18″
14							Unskilled	72′26″
15						Quick breach	Skilled	51′30″
16							Unskilled	63′47″
17		370 mm thick masonry wall	Horizontal breach	1.2 m in diameter	3	Safe breach	Skilled	85′41″
18							Unskilled	98′21″
19						Quick breach	Skilled	74′57″
20							Unskilled	86′11″

Table 6: Rescue time of horizontal and vertical life-saving passages (proficiency: unskilled).

Life-saving passage	Removal time T_{1i}			Breach time T_{2i}		Shoring time T_{3i}		Uplift time T_{4i}	Treatment time T_{5i}	Transporting time	Total rescue time T
Vertical	T_{11} 18′06″	T_{12} 22′11″	T_{13} 22′11″	T_{21} 126′50″	T_{22} 126′50″	T_{31} 189′02″	T_{32} 40′11″	T_{41} 41′02″	T_{5} 45′	T_{6} 40′	671′23″
Horizontal	T_{11} 18′06″	T_{12} 18′06″	T_{13} 22′11″	T_{21} 55′17″	T_{22} 55′17″	T_{31} 189′02″	T_{32} 40′11″	T_{41} 41′02″	T_{5} 45′	T_{6} 40′	524′12″

Table 7: Rescue time of horizontal and vertical life-saving passages (proficiency: skilled).

Life-saving passage	Removal time T_{1i}			Breach time T_{2i}		Shoring time T_{3i}		Uplift time T_{4i}	Treatment time T_{5i}	Transporting time	Total rescue time T
Vertical	T_{11} 18′06″	T_{12} 22′11″	T_{13} 22′11″	T_{21} 81′33″	T_{22} 81′33″	T_{31} 155′44″	T_{32} 28′32″	T_{41} 33′27″	T_5 45′	T_6 40′	528′17″
Horizontal	T_{11} 18′06″	T_{12} 18′06″	T_{13} 22′11″	T_{21} 45′05″	T_{22} 45′05″	T_{31} 155′44″	T_{32} 28′32″	T_{41} 33′27″	T_5 45′	T_6 40′	451′16″

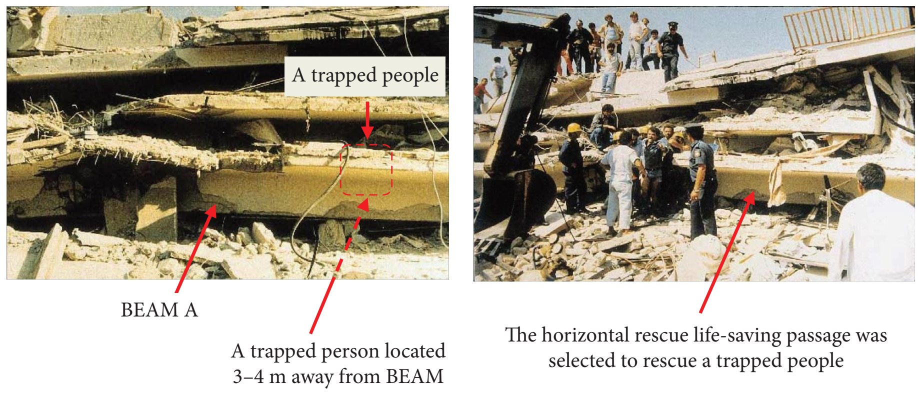

Figure 20: The earthquake rescue site of the RC frame structure [50].

important and long-term significance for the earthquake site rescue. The excavation rescue method is often used to construct the horizontal life-saving passage. The horizontal life-saving passage needs more safety assessment compared with the vertical life-saving passage because the excavation rescue method needs to remove the ruins of supporting the superstructure, which is prone to cause secondary collapse of the ruins. Therefore, the safety assessment of the construction of the life-saving passage should be studied in the follow-up work.

5. The Practicability and Validation Verification of Optimization Method

The earthquake rescue site of RC frame structure ruins in "Technical Handbook for Search and Rescue Operations in Earthquakes", as shown in Figure 20. There are three main steps in the rescue process. First, a part of a RC beam and slab of the floor under investigation were cut off. Contacting with a trapped person located 3–4 m away from the facade. What's more, the horizontal penetration was applied. Some furniture and walling material in building ruins had to be breached and removed in order to reach the trapped person. Finally, it takes about 3.5 hours to reach the trapped people. The removal and breach rescue technologies were adopted in this earthquake rescue. The time is approximate to the timing test of rescue technologies as shown in Tables 2 and 5 in the manuscript, which can reflect the reliability of the timing test to a certain extent. Meanwhile, the main reason why the horizontal life-saving passage was selected is that more floors need not be breached for the pancake-type ruins of RC frame structure. This conclusion is given in "Technical Handbook for Search and Rescue Operations in Earthquakes"; thus, it is possible to avoid using a large number of breach technology in order to decrease the rescue time. However, rescuers should pay attention to the secondary collapse of pancake-type ruins of RC frame structure because some structural and nonstructural components need be removed in the horizontal life-saving passage. Therefore, the safety monitoring of the life-saving passage in building ruins is crucially important to ensure the rescuers as shown in Figures 11 and 17 in the manuscript. Some safety monitor method can also be utilized in the process of earthquake rescue, such as the electronic leveling instrument and wireless sensor can be used to monitor the displacement change of building ruins [50]. Other safety monitor method can also be referenced in the process of earthquake rescue; for instance, Nicola Casagli et al. [51] utilized monitoring equipment to predict landslides and used the displacement and velocity time history of monitoring points as safety discriminant indicators to complete early warnings of landslides. Fabio Pratesi et al. [52] monitored the inclination of the ancient Italian city wall caused by the earthquake and completed a safety evaluation and early warning of the city wall by monitoring the structural displacement and velocity time history response of the wall.

Figure 21: Pancake-type RC frame structure ruins in 2023 Turkey Ms7.8 earthquake [4].

On 6 February 2023, a Ms 7.8 earthquake struck southern and central Turkey and northern and western Syria. A great quantity of trapped people is buried by a large number of collapsed RC frame structures, which has brought great challenges to Search and Rescue team. At that moment, the rescue efficiency is particularly important. Figure 21 is a pancake-type RC frame structure ruins in 2023 Turkey Ms7.8 earthquake [53]. The horizontal life-saving passage can be selected first considering that the probability of secondary collapse of full pancake-type ruins is relatively small under the aftershocks. In addition, the wood shoring should be used to protect ruins from secondary collapse because of removing the building ruins, and simultaneously,

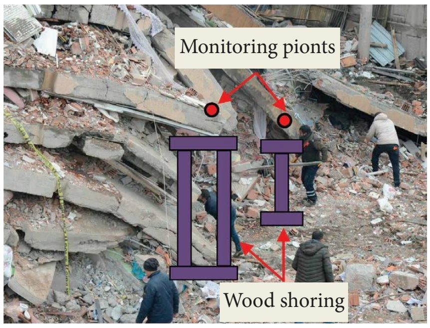

Figure 22: The diagrammatic sketch of shoring and safety monitoring of RC frame structure ruins.

Figure 23: An 7-storey package-type collapse building in Changsha, China in 2022.

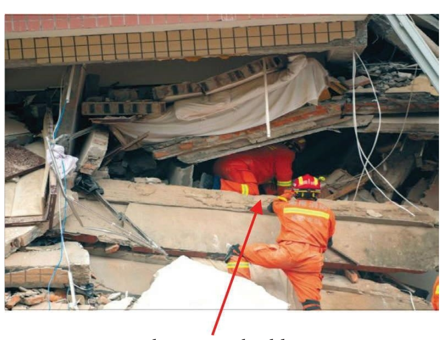

Figure 24: Rescue site of 7-storey package-type collapse building.

it is very necessary to monitor the change of building ruins, as shown in Figure 22.

The method of construction and optimization of life-saving passage is not only utilized to simulate the seismic collapse of building but also other causes of collapse, such as quality problems of buildings, explosions, and hurricanes. For example, an old building collapsed suddenly in Changsha, China on April 29, 2022, due to the illegal construction of the building, and meanwhile, this building is shown as full pancake-type collapse [54], as shown in Figure 23. The vertical life-saving passage can be selected because large hoisting machine can enter the rescue site to adopt the layer-by-layer stripping method. However, considering impact of buildings on both sides, the large number of trapped people, and the urgent rescue time, the horizontal life-saving passage was selected to rescue the trapped people, as shown in Figure 24. Finally, 10 trapped people were rescued. This first rescue life-saving passage plan of pancake-type collapse is consistent with the main conclusion of this paper. In addition, the numerical simulation method in this paper can be adopted to reappear the building ruins scene, then, different rescue life-saving passage can be selected, and finally, the optimization method of rescue life-saving passage can be utilized.

6. Conclusion

The method of constructing and optimizing life-saving passage in building ruins based on numerical simulation is investigated in this paper. The restart function of ANSYS/LS-DYNA is mainly used to re-edit the numerical model of the building ruins to construct the life-saving passage through the realization of rescue technology. The optimization method of constructing the life-saving passage is proposed; similarly, the optimal calculation formula is given according to the timing test of the rescue technology. The main conclusions are as follows:

(1) The restart function of ANSYS/LS-DYNA is utilized to re-edit the structural components of the building ruins, which can construct the life-saving passage effectively and quickly.

(2) The structural components elements of numerical models of building ruins are deleted, added, and loaded to realize removal or breach, shoring, and breach technology, which can construct the life-saving passage, and simultaneously, the life-saving passages of different rescue routes are constructed with RC frame structure ruins as the research object.

(3) The combination of rescue technologies with the shortest time is taken as the optimal route of constructing life-saving passage based on the premise of “double safety” of rescuers and trapped people. The method can give the optimal route of life-saving passage intuitively and accurately.

(4) The construction of the horizontal life-saving passage is superior to the vertical life-saving passage when the RC frame structure formed pancake-type ruins under the earthquake, because it takes more rescue time to construct the vertical life-saving passage through using the breach rescue technology in the layered rescue method.

(5) It is very necessary to monitor the safety of building ruins when the horizontal life-saving passage is constructed.

(6) The rescue efficiency can be greatly improved when the rescuers have skilled rescue techniques. Thus, the rescue training is great importance and long-term significance for the earthquake site rescue.

(7) The timing test of rescue technology should be further studied considering more influencing factors in the actual earthquake rescue process.

(8) The safety evaluation of the life-saving passage affects the "double safety" of the rescuers and trapped people directly, which is a very valuable research.
(9) The method of FEM and F-DEM and restart function of LS-DYNA program can be attempted to construct a life-saving passage for building collapse caused by other reasons, such as quality problems of buildings, explosions, and hurricanes.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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