Article

Development of Decision-Making Factors to Determine EMP Protection Level: A Case Study of a Brigade-Level EMP Protection Facility

Kukjoo Kim and Young-Jun Park *

Department of Civil Engineering and Environmental Sciences, Korea Military Academy, Seoul 01805, Korea; kukjoo.kim@mnd.go.kr

* Correspondence: parky@mnd.go.kr; Tel.: +82-2-2197-2955

Abstract: This study developed decision-making factors to classify electromagnetic pulse (EMP) protection levels and determine various protection measures. We proposed three EMP protection levels of 80, 60, and 40 dB by considering the characteristics of military equipment and factors that determine EMP protection level, based on a Delphi study. We modeled EMP protection facilities for brigade-level troops to evaluate the derived decision-making factors and applicability of differential protection levels. The natural attenuation effect of soil was confirmed for structures installed underground. The shielding effect of wet soil was up to 30 dB. Considering the 20 dB EMP resistance of military equipment and the 30 dB of attenuation of wet soil, new materials with 30 dB of shielding efficiency could be used to meet an EMP protection level of 80 dB. Therefore, we confirmed that EMP protection measures could be established to build mobile, lightweight shelters. If lightweight shelters are constructed by applying the differential protection level scheme, they can be applied as a more effective EMP protection measure. Furthermore, differential protection measures can be adopted as a sustainable defense facility policy approach, wherein lightweight protection facilities replace conventional heavyweight facilities.

Keywords: electromagnetic pulse (EMP); shielding effectiveness (SE); EMP protection level; EMP protection facility; METT + TC

Citation: Kim, K.; Park, Y.-J. Development of Decision-Making Factors to Determine EMP Protection Level: A Case Study of a Brigade-Level EMP Protection Facility. *Appl. Sci.* **2021**, *11*, 5227. <https://doi.org/10.3390/app11115227>

Academic Editors:

Hyeon-Jong Hwang, Il-Woo Nam and Jang-Woon Baek

Received: 28 April 2021

Accepted: 2 June 2021

Published: 4 June 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

1.1. Background

Recently, the nuclear capability of North Korea was demonstrated through nuclear and missile tests [1]. Therefore, electromagnetic pulse (EMP) threats have increased in South Korea. North Korea is intensively developing asymmetric strategic weapons, as demonstrated by the sixth nuclear test and missile transporter erector launcher tests. On 3 September 2017, immediately after the sixth nuclear test, North Korea claimed that they were capable of attacking with an ultra-powerful EMP by detonating a hydrogen bomb high in the atmosphere [2].

Based on this, it was predicted that North Korea would aim to maximize an EMP effect that could destroy infrastructure systems such as electric power, telecommunications, and finances, rather than nuclear provocation for the purpose of killing people. In September 2017, the U.S. EMP Commission issued a statement acknowledging the development and possession of hydrogen bombs capable of generating EMP by North Korea.

Furthermore, electronic weapons can be used to generate EMP intentionally in major information and telecommunication infrastructures to threaten the underlying systems [3]. Thus, the threat of disrupting or destroying electric/electronic devices and communication systems using non-nuclear weapons such as electronic bombs and high-power EMP generators is increasing [4]. As EMP threats have increased globally, South Korea has recognized the risks of EMPs and is thereby developing and implementing EMP-related laws, policies,

and projects [5]. However, they are still in their infancy. In the field of EMP protection, there are few construction cases, limited to some military and public organizations. If radio wave monitoring work for aviation, maritime, GPS, etc. in the private sector is paralyzed, along with military threats, it may lead to major national crises and social chaos such as threats to the safety of people and national security [6–9].

Currently, most EMP protection facilities in South Korea conform to the EMP protection technology and test method standards (MIL-STD-188-125, etc.) of the U.S. Department of Defense [10]. Based on strict applications, South Korea is very reluctant to apply newly developed materials or differential application plans, based on the importance of facilities. If shielding facilities applying the MIL-STD-188-125 standard are installed in all national infrastructures, it is estimated that a huge budget will be required. MIL-STD-188-125 does not consider the blocking and attenuation characteristics of regular buildings or underground facilities in terms of EMP protection. Furthermore, it requires the use of a huge amount of concrete, rebar, and steel plates in heavyweight structures to disallow even a single failure in mission-critical facilities. Hence, there is no need to apply MIL-STD-188-125 to military facilities of all echelons. However, various construction materials and protection levels should be applied to various military facilities based on a flexible analysis of their criteria. By reducing the use of concrete and steel on this basis, it is possible to implement carbon neutrality and green planning [11–13]. In construction projects, the use of concrete and steel account for 65% of building greenhouse gas (GHG) emissions [14], out of which the use of concrete accounts for 40% of CO₂ emissions [15]. In particular, the mean embodied carbon dioxide (ECO₂) of buildings is 340 kg-CO₂/m², accounting for approximately 60% of all structures [16]. This means that reducing the ECO₂ of structures is the same as reducing GHG emissions, which contributes to carbon neutrality [17–20]. The application of green planning to EMP protection, especially in the military, is a very important policy basis in national defense that contributes to the green growth policy of the South Korean government because the military plays a leading role in the development and domestic application of EMP protection technologies [21]. Moreover, the use of a variety of levels of EMP shielding effectiveness and shielding materials is very advantageous for the military, as they facilitate flexibility in military operations.

In this study, we differentiated EMP protection levels using a method of optimizing the military operation environment and available assets as compared to the conventional EMP protection method, and we developed decision-making factors for determining protection levels. Based on this, we modeled brigade-level, underground EMP protection facilities, simulated their EMP-shielding performance to develop an EMP shielding method suitable for strategic and tactical troops, and applied it to national defense policies.

1.2. Objectives and Scope

The main goal of this study was to develop decision-making factors that could be used to determine EMP protection level. A group of EMP protection experts from the military and private sector was set up, and the Delphi method was used to derive a differential EMP protection method. The derived decision-making factors were applied to model brigade-level EMP protection facilities for the military. Based on this, the protection-level differentiation method of EMP protection facilities was analyzed.

2. Overview of Nuclear EMP

A high-power EMP refers to an EMP with powerful energy, such as a nuclear EMP generated by a nuclear explosion at a high altitude or a non-nuclear EMP produced by an artificial generator. For nuclear EMPs, up to 50 kV/m is generated over a broadband of several Hz to several GHz. Here, 50 kV/m is defined by U.S. military standards (MIL-STD) and International Electrotechnical Commission (IEC) standards. When the distance between two points is 1 m, the mutually induced voltage is 50,000 V [22,23]. The generated EMP causes a flow of strong electric currents in electronic circuits in electric/electronic devices and communication systems, thus destroying them in a form of flashover or melting.

As shown in Figure 1, EMPs are classified into nuclear EMPs (high-altitude nuclear EMPs) and non-nuclear EMPs. However, non-nuclear EMPs include lightning EMPs (LEMPs) and geomagnetic storms, which are naturally occurring phenomena and distinguished from artificially generated nuclear EMPs and HPEMs.

Figure 1. Classification of EMPs.

For nuclear EMPs, gamma rays produced by a nuclear explosion at a high altitude (usually higher than 30 km in the sky) collide with the atmosphere and radiate high-energy EMPs, which cause damage to a broad area. Specifically, high-power EMPs are produced due to the enormous energy generated by the powerful flash that persists from between several seconds to several minutes after a nuclear explosion. Although it has no fatal effect on human bodies, it causes a flow of overcurrent, momentarily, in various electric/electronic devices, communication systems, power control systems, aviation control systems, etc., thereby paralyzing their functions. A nuclear explosion produces a very short and intensive nuclear EMP. As instantaneous EMP currents are induced on all kinds of metal conductors, the currents may penetrate the equipment or damage electric/electronic devices, resulting in their failure.

The EMPs generated at a low altitude can be considered to be similar to HEMPs, but the characteristics of the radiation are different. To produce nuclear EMPs, a nuclear weapon must be detonated above the atmosphere. Although there is no distinct boundary to the atmosphere, the typical properties of nuclear EMPs are shown when detonation occurs at an altitude higher than 30 km. In other words, in the case of a nuclear explosion occurring at a low altitude (approximately below 20 km), the generation of a high-power EMP is less because the density of air molecules is high. However, it can be said that the physical impact of the radioactive storm and fallout is larger than that of high-power EMPs. The generated high-power EMP spreads as if a circular shape centered on the explosion point is expanding continuously. The thickness of the circular shape reaches tens of meters. If the circular shape reaches the Earth's surface, a short EMP can be felt, and after several nano-seconds, the high-power EMP increases. After several hundred nano-seconds, all electric and electronic devices stop working. High-power EMPs exist in a high-frequency band between tens of MHz and tens of GHz. The high-power EMP caused by a nuclear explosion is distributed in a wide range from a low-frequency band to hundreds of MHz.

3. Development of Decision-Making Factors to Determine the EMP Protection Level

Recently, a study was conducted on the differentiation of EMP protection levels to reduce the construction costs and times of EMP protection facilities in the South Korean military and to implement efficient protection measures [21]. As a result of conducting a Delphi analysis with 21 EMP protection experts from the military and private sector, it was confirmed that a vulnerability analysis for EMP attacks should be performed first to differentiate EMP protection levels. Along with this, the damage recovery time for an EMP attack was derived as an essential factor of the EMP protection vulnerability analysis. In other words, it was confirmed that EMP protection measures and protection

levels could be applied discriminately, according to the time required for recovery. Table 1 summarizes the research results conducted by Kim et al. [21]. As shown in Table 1, a variety of factors were derived such as the missions of troops, terrain conditions, threat factors, and available troops.

Table 1. Decision-making factors to determine EMP protection level.

Factor	Description
Time	Recovery time of damaged equipment should be considered. The replacement time of the damaged equipment should be considered. The price of the equipment affected by the EMP should be reflected.
Enemy	The tolerance of the equipment attacked by the EMP should be considered. Type of damage (loss, recovery cost, etc.) due to the EMP attack should be considered. The allowable damage level due to the EMP attack should be considered.
Mission	The impact on emergency activity (military, civil defense, etc.) due to equipment failure by EMP attack should be considered.
Troops	Construction costs of EMP protection should be considered. The possibility of recovering the damaged equipment should be considered. The ease of recovery of the damaged equipment should be considered. The possibility of replacing the damaged equipment should be considered. The ease of replacement of the damaged equipment should be considered.
Terrain	The environmental condition (underground, geological, etc.) where the equipment attacked by the EMP is located must be considered. The characteristics of the EMP protection facility (concrete, underground, etc.) should be considered.

Using the decision-making factors mentioned in Table 1, the importance of EMP protection facilities was selected based on their levels. It was important to select an appropriate protection level for the characteristics of each echelon using EMP protection facilities. The selection criteria of the importance levels are shown in Table 2.

Table 2. Importance level of EMP protection.

Importance Level	Description
High	A facility where even a simple malfunction is not allowed. In the event of failure, the recovery to normal conditions requires a lot of time and effort, which may cause huge damage. A facility where large-scale damage may occur if important data are lost due to failures or errors.
Medium	A facility where a simple malfunction is allowed. A case in which performance degradation occurs, but quick recovery is possible. If software and hardware malfunctions occur, normal function can be recovered via rebooting and program modifications.
Low	A facility where hardware failures are allowed. In the event of the hardware being damaged, it can be repaired in a prescribed time. In the event of the hardware being damaged, important data are not damaged/lost or appropriate measures have been prepared.

By evaluating the EMP resistance of electronic devices based on the protection importance levels mentioned in Table 2, we selected 30 V/m for the minimum electric field strength showing simple malfunctions [24] and 1 kV/m for the minimum level showing hardware damage [25]. Based on these experimental results and expert advice, it was confirmed that the shielding standards could be established by subdividing the EMP differentiation standards of the military into Levels 1, 2, and 3 as shown in Table 3.

Table 3. Radioactive protection performance standards.

Protection Level	Frequency Range	Shielding Standard (dB)
Level 1	10 kHz~10 MHz 10 MHz~1 GHz	$20 \log f - 60$ or higher 80
Level 2	10 kHz~10 MHz 10 MHz~1 GHz	$20 \log f - 80$ or higher 60
Level 3	10 kHz~10 MHz 10 MHz~1 GHz	$20 \log f - 100$ or higher 40

4. Case Study for a Brigade-Level EMP Shelter Using the Finite Integrating Method

The materials and structure of the building should be identified to estimate and simulate the EMP damage range for the building. The simulation programs used for numerical analysis of buildings can be classified mainly into four methods: the method of moment (MoM), the finite element method (FEM), the finite difference time domain (FDTD), and the finite integrating method (FIM). Among various analysis programs, Feko is a typical commercial numerical analysis program that uses MoM. Although Feko provides robust analyses for large buildings, it requires a lot of analysis time for a system structure mixed with small buildings. The high-frequency structure simulator (HFSS) is based on FEM. Although the HFSS can segment meshes according to their shape, it can perform a suitable analysis of a building, regardless of its shape, based on the high-frequency band numerical analysis method, and provide excellent accuracy. However, for complex or large buildings, the analysis time is longer compared to other programs [26].

SEMCAD is a commercial representative analysis program using the FDTD method that does not require repeated analysis (analysis characteristics of FDTD). Furthermore, the FDTD algorithm is simple and can be implemented efficiently and easily. As not only the building but also the surrounding environment of the building must be considered, the program execution time is long. Furthermore, if the building shape is curved, there is a limitation to linking with other programs.

Microwave Studio (MWS) is a commercial program that uses FIM, which is a new analysis algorithm different from conventional methods. MWS is capable of processing curved boundaries and complex shapes. Moreover, it produces analysis results quickly. Therefore, in this study, we used MWS to calculate the EMP protection performance of brigade-level protection facilities and apply the differentiation application measures.

Natural shielding efficiency against an EMP was modeled for the computer room among various brigade-level facilities on the ground and underground by assuming that it was an EMP shielding facility. The underground soil condition was classified into dry soil and wet soil, considering the terrain characteristics of South Korea. As the EMP-shielding efficiency of concrete walls varies depending on reinforcement configuration, a standard type of reinforcement configuration (15 cm $\times$ 15 cm) was assumed. Figure 2 shows the geometric design of the modeled EMP rooms.

The EMP shielding rooms comprised office rooms, a communication room, a control room, and an equipment room in a building having dimensions of 13 m $\times$ 13 m $\times$ 2.7 m. Among various components of the building, four windows were physically most vulnerable to high-power EMPs. Additionally, the building had one main entrance, which was also vulnerable.

For the simulation settings, four bands, i.e., 10 kHz, 10 MHz, 100 MHz, and 500 MHz, were applied among analysis frequencies ranging from 10 kHz to 1 GHz, which were signal characteristics of nuclear EMPs, described in IEC-61000-2-9. Additionally, for demonstrating the maximum intensity of E1 pulses, a 50 kV/m pulse was applied. E-field probes were installed at seven places to identify EMP attenuation characteristics, as shown in Figure 3. As shown in Figure 4, air and soil were modeled to show the radiation of the E1 pulse. Figure 5 shows the waveform and maximum intensity of the E1 pulse. Table 4 shows the input values and material properties for air, dry soil, and wet soil conditions.

Figure 2. Developed FIM model.

Figure 3. Sensor locations.

(a) Case 1—Air condition

(b) Case 2—Dry and wet soil conditions

Figure 4. Simulation conditions (a) Case 1—Air condition, (b) Case 2—Dry and wet soil conditions.

Figure 5. E1 pulse shape used in simulation.

Table 4. Input values used in FIM.

Input Value	Air	Dry Soil	Wet Soil
Density (kg/m ³)	1.204	1550	1800
Thermal conductivity (W/K/m)	0.026	0.2	1
Heat capacity (kJ/K/kg)	1.005	0.8	1.5
Diffusivity(m ² /s)	2.14872×10^{-6}	1.6129×10^{-7}	3.7037×10^{-7}

In the simulation results, high electric field strength was measured around the windows for the ground structure, as expected. The incoming high-power EMP refracted by hitting the walls, ceiling, and floor inside the communication room. In the underground structure, the natural attenuation effect of soil was confirmed, and the wet soil with high electrical conductivity showed a better attenuation effect. As shown in Table 5, the wet soil produced a natural attenuation effect of up to 30 dB. Figure 6 shows the electric field strength attenuation by measurement locations over time.

Table 5. Measurement results of natural shielding effectiveness against E1 Pulse.

Shielding Effectiveness	Air	Dry Soil	Wet Soil
Room 1	13.8 dB	15.18 dB	22.15 dB
Room 2	17.99 dB	22.85 dB	31.70 dB
Room 3	17.45 dB	23.60 dB	28.40 dB
Room 4	18.96 dB	23.87 dB	34.24 dB
Corridor 1	17.45 dB	19.82 dB	25.41 dB
Corridor 2	11.50 dB	12.11 dB	19.41 dB
Corridor 3	21.13 dB	24.00 dB	30.22 dB

(a) Electric field distribution of E1 pulse.

(b) Electric field level of Room 1.

(c) Electric field level of Room 2.

(d) Electric field level of Room 3.

(e) Electric field level of Room 4.

(f) Electric field level of Corridor 1.

Figure 6. Cont.

Figure 6. Analysis results of electric field strength attenuation based on measurement location (a) Electric field distribution of E1 pulse, (b) Electric field level of Room 1, (c) Electric field level of Room 2, (d) Electric field level of Room 3, (e) Electric field level of Room 4, (f) Electric field level of Corridor 1, (g) Electric field level of Corridor 2, (h) Electric field level of Corridor 3.

5. Discussion

As shown in the results of this study, the shielding standard of a uniform 80 dB in the South Korean military requires only protection facilities with shielding rooms. However, for common protection facilities of the military, underground or semi-underground structures have been built to ensure initial survivability. Nevertheless, a fixed form of permanent EMP shielding facility is not suitable for division or brigade-level troops because they conduct military operations by frequently moving their stations. Furthermore, they are not required to have a strategic level of capability that does not allow malfunctions of their command-and-control equipment. As momentary failures or simple malfunctions can be repaired within an acceptable time, the differential EMP shielding standard can be applied. Considering the 20 dB of EMP resistance of military equipment and the 30 dB of attenuation of wet soil, new materials with 30 dB shielding efficiency can be used to meet the EMP protection level of 80 dB. For example, it is possible to construct a EMP protection facility using various materials that satisfy the minimum shielding effectiveness of 30 dB such as shielding paper, film, and fabrics. Therefore, we confirmed that EMP protection measures could be established to build mobile lightweight shelters. Moreover, lightweight structures using shielding fabrics will be more effective than the shielding rooms of heavyweight structures using steel plates for the brigade level or lower. If EMP protection facilities built in the future are replaced with lightweight protection facilities, then a large amount of concrete and steel will be saved. If lightweight shelters are constructed by applying the differential protection level scheme, they can be applied as more effective EMP protection measures. Furthermore, differential protection measures can be adopted as a sustainable defense facility policy approach, wherein lightweight protection facilities replace conventional heavyweight facilities.

6. Conclusions

In this study, we derived decision-making factors to determine a differentiation and diversification scheme for the current, uniform EMP protection standard of 80 dB. Based on a Delphi analysis, factors of response–recovery time were identified in terms of the mission, threat, terrain, characteristics of troops, and equipment as factors that needed to be considered for the construction of differential EMP protection facilities. Based on these factors, it was confirmed that differential levels of 80 dB, 60 dB, and 40 dB could be determined according to the characteristics of the troops and equipment. To assess the

constructability of differential EMP protection facilities, simulations were conducted for the communication room of a brigade-level force. As a result, high electric field strengths were measured around the windows for the ground structure, and the incoming high-power EMP refracted inside the communication room and spread out evenly on all sides. For the underground structure, the natural attenuation effect of the soil was confirmed, and the wet soil with high electric conductivity showed a natural attenuation effect of up to 30 dB.

Therefore, it was confirmed that EMP protection measures could be changed from the current shielding room-oriented, fixed-type protection facilities to mobile lightweight protection facilities using shielding fabrics, shielding racks, redundant equipment, spare equipment, and failure recovery. If differential protection levels are applied to the EMP protection facilities required by the military, then it will be possible to replace the current, fixed-type, heavyweight protection facilities and establish more practical protection measures against EMP threats. Furthermore, if heavyweight protection facilities are replaced with lightweight protection facilities along with various protection levels, it will be a more effective EMP protection measure for mobile forces at the brigade level or lower. If multiple EMP protection facilities built in the future are replaced with lightweight protection facilities, a large amount of concrete and steel will be saved, which will be a sustainable defense facility policy direction.

Author Contributions: Conceptualization, Y.-J.P. and K.K.; Methodology, K.K.; Software, Y.-J.P.; Validation, Y.-J.P. and K.K.; Formal Analysis, K.K.; Investigation, Y.-J.P.; Resources, Y.-J.P.; Data Curation, Y.-J.P. and K.K.; Writing—Original Draft Preparation, K.K.; Writing—Review & Editing, Y.-J.P.; Visualization, Y.-J.P.; Supervision, Y.-J.P.; Project Administration, K.K. and Y.-J.P.; Funding Acquisition, Y.-J.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by a grant (21SCIP-B146652-04) from the Korea Agency for Infrastructure Technology Advancement.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This work was supported by the research fund of the Korea Agency for Infrastructure Technology Advancement. The ROKA Nuclear-WMD Protection Research Center at the Korea Military Academy is gratefully acknowledged for providing the support that made this study possible.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Edwards, P.J.; Reid, P.S. Effects of nuclear explosion starfish prime observed at Hobart, Tasmania. *J. Geophys. Res.* **1962**, *69*, 3607–3612. [[CrossRef](#)]
2. Islam, T. Collisional effects in simulation of high altitude nuclear explosion. In Proceedings of the 55th Annual Meeting of the APS Division of Plasma Physics, Denver, CO, USA, 11–15 November 2013; Volume 58.
3. Pawar, S.P.; Rzeczkowski, P.; Potschke, P.; Krause, B.; Bose, S. Does the processing method resulting in different states of an interconnected network of multiwalled carbon nanotubes in polymeric blend nanocomposites affect EMI shielding properties? *ACS Omega* **2018**, *3*, 5771–5782. [[CrossRef](#)] [[PubMed](#)]
4. Shahzad, F.; Alhabeb, M.; Hatter, C.B.; Anasori, B.; Hong, S.M.; Koo, C.M.; Gogotsi, Y. Electromagnetic interference shielding with 2D transition metal carbides (MXenes). *Science* **2016**, *353*, 1137–1140. [[CrossRef](#)] [[PubMed](#)]
5. Cho, G.; Cheon, J. Study on defense measure of EMP of nuclear and electromagnetic pulse weapon. *Def Tech* **2007**, *345*, 52–59. (In Korean)
6. Jacob, G. The Swiss EMP concept of general defense. *IEEE Antennas Propag. Soc. Newsl.* **1987**, *29*, 5–10.
7. Ministry of National Defense. *Department Military Facilities Criteria 2-20-30: Design Criteria for EMP Protection Facilities*; Defense Installation Agency: Seoul, Korea, 2019.
8. National Cyber Security Center, National Radio Research Agency, National Security Research Institute. *Technical Standard of EMP Attack Prevention Measures*; National Security Research Institute: Seoul, Korea, 2018.

9. Ministry of Science and ICT. *Evaluation Criteria for Major Telecommunication Infrastructure against EMP Attack*; Ministry of Sciences and ICT: Sejong City, Korea, 2018.
10. Department of Defense Interface Stand. *High-Altitude Electromagnetic Pulse (HEMP) Protection for Ground-based C4I Facilities Performing Critical, Time-Urgent Mission: Part 1 Fixed Facilities*; MIT-STD-188-125-1; Departments and Agencies of the Department of Defense: Washington, DC, USA, 1998.
11. Kim, J.J.; Goodwin, C.W.; Kim, S.K. Communication turns green construction planning into reality. *J. Green Build* **2017**, *12*, 168–186. [\[CrossRef\]](#)
12. International Energy Agency and the United Nations Environment Programme. *2018 Global Status Report: Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector*; International Energy Agency and the United Nations Environment Programme: New York, NY, USA, 2018; p. 9. Available online: <https://www.worldgbc.org/sites/default/files/2018%20GlobalABC%20Global%20Status%20Report.pdf> (accessed on 3 August 2020).
13. Pacheco-Torgal, F.; Cabeza, L.; Labrincha, J.; De Magalhaes, A. *Eco Efficient Construction and Building Materials: Life Cycle Assessment (LCA), Eco-Labeling and Case Studies*; Elsevier: Cambridge, UK, 2014; pp. 624–630.
14. Kim, K.J.; Park, Y.J. Development of design considerations as a sustainability approach for military protective structures: A case study of artillery fighting position in South Korea. *Sustainability* **2020**, *12*, 6479. [\[CrossRef\]](#)
15. Clark, D.; Bradley, D. *Information Paper—31: Embodied Carbon of Steel versus Concrete Buildings*; Cundall Johnston and Partners LLP: Newcastle, UK, 2013; p. 4.
16. Lee, I.J.; Yu, H.; Chan, S.L. Carbon Footprint of Steel-Composite and Reinforced Concrete Buildings, Standing Committee on Concrete Technology Annual Concrete Seminar 2016, Hong Kong, 20 April 2016; Construction Industry Council. Available online: https://www.devb.gov.hk/filemanager/en/content_971/7_Carbon_Footprint_for_Steel_Composite_and_Reinforced_Concrete_Buildings.pdf (accessed on 20 November 2020).
17. Kim, S.K.; Kim, M.H. A study on the development of the optimization algorithm to minimize the loss of reinforcement bars. *J. Archit. Inst. Korea* **1991**, *7*, 385–390.
18. Lee, D.H.; Lee, S.G.; Kim, S.K. Composite phase-change material mold for cost-effective production of free-form concrete panels. *J. Constr. Eng. Manag.* **2017**, *143*, 1–13. [\[CrossRef\]](#)
19. Kim, S.K.; Hong, W.K.; Joo, J.K. Algorithms for reducing the waste rate of reinforcement bars. *J. Asian Archit. Build.* **2004**, *3*, 17–23. [\[CrossRef\]](#)
20. Hwang, J.W.; Park, C.J.; Wang, S.K.; Choi, C.H.; Lee, J.H.; Park, H.W. A Case Study on the Cost Reduction of the Rebar Work through the Bar Loss Minimization. In Proceedings of the KIBIM Annual Conference 2012, Seoul, Korea, 19 May 2012.
21. Kim, K.J.; Park, S.W.; Baek, J.W.; Park, Y.J. A study on the method for judging the EMP protection plan and required level through decision making. *J. Korea Inst. Build. Constr.* **2019**, *19*, 193–200. (In Korean)
22. Kim, H. Truth of EMP threat and development plan. *Def Tech* **2013**, *414*, 98–103. (In Korean)
23. Choi, T.; Cho, W. Countermeasure of electromagnetic pulse (EMP). *Def Tech* **1992**, *157*, 54–59. (In Korean)
24. IEC TR 61000-1-3. *General-The Effects of High-Altitude EMP (HEMP) on Civil Equipment*; International Electrical Commission: Geneva, Switzerland, 2002; pp. 21–34.
25. IEC TR 61000-1-5. *General-High Power Electromagnetic (HEMP) Effects on Civil Equipment*; International Electrical Commission: Geneva, Switzerland, 2004; pp. 21–35.
26. Gu, S.; Lin, T.; Lasri, T. Materials characterization by near-field scanning microwave microscopy. In Proceedings of the 2016 Progress in Electromagnetic Research Symposium (PIERS), Shanghai, China, 8 August–11 September 2016.