Análisis comparativo en base a la sostenibilidad ambiental entre bóvedas de albañilería y estructuras de hormigón

Comparative analysis on environmental sustainability between masonry vaults and concrete structures

Justo García Sanz Calcedo*¹, Manuel Fortea Luna*, Antonio M. Reyes Rodríguez*

* Universidad de Extremadura. ESPAÑA

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Resumen

En este trabajo se compara desde una perspectiva de sostenibilidad, el impacto medioambiental de una estructura de fábrica horizontal de albañilería mediante bóveda de arista, respecto a un forjado estructural de hormigón armado de tipo reticular, utilizando técnicas basadas en el Análisis del Ciclo de Vida para cuantificar la energía consumida en el proceso de fabricación de los materiales y construcción de la estructura. Se ha detectado que la bóveda consume un 75% menos de energía en el proceso de construcción, emite un 69% menos de CO₂ a la atmósfera, tienen un coste medio de fabricación para pequeñas luces similar al de un forjado convencional e inferior cuando se trata de salvar grandes luces, genera un 171% menos de residuos procedentes de embalaje en obra, aunque es necesario mas cantidad de mano de obra y que ésta sea más especializada. Se demuestra que la construcción abovedada satisface con creces las exigencias actuales en cuanto a sostenibilidad, así como que esta técnica constructiva puede convivir con la tecnología propia de la sociedad actual, dando como resultado un producto de altas prestaciones económicas, funcionales y energéticas.

Palabras Clave: Construcción sostenible; eficiencia energética; ecodiseño; ACV; bóveda

Abstract

This paper compares, from a sustainability perspective, the environmental impact of a masonry arris vault with respect to a reticulated reinforced concrete slab, using techniques based on the Life Cycle Assessment to quantify the energy used in the manufacturing process of materials and in the construction of the structure. It has been detected that the vault consumes 75% less energy in the construction process, it emits 69% less CO₂ into the atmosphere, it has an average manufacturing cost for short spans similar to a conventional slab, but much lower when large spans have to be covered, and it generates 171% less packaging waste from works, but it needs a larger and more skilled labor force. This paper shows that the vaulted building fully meets the current sustainability requirements and that this construction technique can coexist with the technology characterizing today's society, resulting in a product with high economic, functional and energy performances.

Keywords: Sustainable building; energy efficiency; eco-design; LCA; vault

1. Introducción

1. Introduction

Practically all buildings in the developed countries are built with reticulated reinforced concrete structures, with unidirectional slabs. The use of vaults as a support element became obsolete during the first third of the 20th century, being used only in the reconditioning of historical buildings (Di Cristiano Crucianelli, L. et al., 2000), or rustic constructions. Nevertheless, in Extremadura there are still several vaulted constructions; its inhabitants, especially in the rural environment, spend a great deal of their lives sheltered in this type of houses, churches, institutional buildings, and simple work or assembly places.

¹ Autor de correspondencia / Corresponding author:
E-mail: jgsanz@unex.es

The vault (Moya and Blanco, 1993) is seen permanently in every place: arcaded squares, houses of the encomienda, convents, hermitages, water and snow wells, drying sheds, cemeteries, cisterns, flour mills, ovens, chain pump wells, bridges, oil-mills, mills, pens, stables, pigpens, drains, and so on. Such a proliferation can be neither capricious nor casual; it is rather the expression or result of finding an efficient and versatile structure, which is able to solve a wide range of situations with little resources (Fortea and López Bernal, 2001).

Reinforced concrete is a relatively new technology that was quickly adopted and with great virulence, eliminating all competitors in a ravaging way. The first news regarding its existence dates from the middle of the 19th century, when William Willkinson patented a system with iron reinforcements in the interior (Miquel López, 2008). For half a century it underwent an experimentation period, bursting in strongly at the beginning of the new century. The first building with reinforced concrete was built in 1900.

In 1913, prepared concrete was supplied in Baltimore (USA) for the first time, and three years later the truck mixer as we know it today showed up. In 1929, Wright built the first concrete skyscraper, and in 1958, the New York Dodge Corporation published "The Structures of Eduardo Torroja", a genuine "bible" of reinforced concrete, a mandatory text for all engineers and architects intending to design any kind of construction. In Spain, the first corporate building built with reinforced concrete was the flour manufacturing company La Ceres in Bilbao, from 1899-1900.

Even today, after the approval of the Spanish Technical Construction Code in 2006, as an almost encyclopedic compendium of all construction techniques (CTE, 2007), vaults are still missing in that document. The juridical regulatory field does not acknowledge the existence of vaults, which practically means that it is forbidden to use them as a structural part of a building, remaining only as a decorative element.

The arch, and its derivations the vault and the dome (Huerta, 2004), is one of the most ingenious constructive resources produced by the human being in "its long struggle against tractions" (León González, et al; 2007). The builder, conditioned by the need to use rocky materials, had to use his wits to discover new ways for ensuring stability and durability, harmonizing this purpose with that of feasibility and economy of the constructive process.

Until now, the market competition between traditional brick structures and reinforced concrete structures has given a victory for the latter, apparently for cost reasons (Heyman, 1995). Climate change, CO₂ emissions, and the global energy market, force us to make new approaches with regard to resources. Currently, we should consider the energy balances in all processes, the emission of contaminant gases, and residues' emissions, in addition to the strictly economical balances, which force us to monetize the harmful effects on the environment.

The energy consumed in the manufacturing and building processes is a factor inherent to all types of activities; it implies changes in the environment and results in a series of known environmental impacts. For example, fossil energy consumption entails the emission of CO₂ into the atmosphere, which can contribute to the planet's global warming. The building sector represents one of the sectors with the greatest bearing on the carbon dioxide emissions into the atmosphere, mainly due to the high energy consumption (Ministry of Economy, 2003).

Although there are many available data from studies that have evaluated the construction energy consumption and its associated environmental impact (Cuadrado-Rojo and Losada-Rodríguez, 2007), no references on the vaulted systems based on traditional building have been found, except for previous works developed by the authors (Rodríguez, 2010; Fortea and López, 1998).

The purpose of this paper is to compare, from a sustainability perspective, the environmental impact of a structural slab made with reticulated reinforced concrete, with horizontal masonry structure through arris vault, using Life Cycle Assessment techniques to quantify the energy consumed in the manufacturing process of the materials, the structure's building process, and other variables directly related with the constructive process.

2. Methodology

In order to analyze how the structure typology influences the environmental variables, a set of vaults and reticulated slabs with different span hypothesis were selected, whose typology and composition are described at length in paragraph 2.1.

Next, a set of calculation and load hypothesis were defined, which were the base for calculating each structure, thus creating a modular pattern of 4x4, 5x5, 6x6, 7x7 and 8x8 to analyze the behavior of these structures as the interaxial distance increases.

Once the efforts and loads of each one of the former structures were identified, we went ahead with sizing their dimensions, and later on an inventory of materials, labor force and auxiliary means composing the structure was made. Next, a life cycle inventory of each material was carried out, using the Life Cycle Assessment techniques described in the following paragraphs.

2.1 Analyzed Typologies

In the study we used arris vaults with square plans, 1/5 rise-span ratio elliptic section with a layer edge of 0.06m. That is, in a 5x5 vault, at a length of 5m, a deflection of 1.67m is needed. It is a bricked or Catalan vault (Riccardo Gulli, 1995), made of several layers; the first bricked layer is put upright and uses gypsum mortar, and the successive layers are also made with bricks but uses lime mortar (Truñó Ruseñol, 2004). In the spandrels it has a structural fill and the rest, until the top horizontal plan is obtained, is a loose fill. The characteristic of this vault is that it does not need an auxiliary formwork during its construction (Albarrán, 1885), because the fast gypsum set of the first layer allows it to be self-supporting, and therefore it does not need a provisional support. The model has left out the vault's counterforts (element which supports the horizontal thrusts transmitted by the vault), and they have been replaced by metallic beams to obtain balance.

The structural function of the fill is to distribute the loads applied to the platform towards the resistant vault, to confine the latter, and to serve as resistant element when the pressure line, for certain directrices and load conditions, fall out of the vault itself (Martínez et al., 2001).

As base of the masonry structure, a simple hollow brick was used, whose dimensions were 24x12x3cm and its specific weight was 12.07kN/m³, so that each piece did not exceed the value of 11N.

This is a relevant feature, because the weight must not exceed the value which cannot support itself only by the gypsum adherence until the row is completed. If we take into account that each brick is “glued” on both sides in the first layer, this means a contact surface of 108 cm^2 , so the gypsum works at a shear stress of 0.102 N/cm^2 . The brick’s resistance is not a determinant value since the brick works at very low tensions in the vault.

As a concrete structure model, a reticulated slab of 25 cm measured upright was chosen, formed by reinforced concrete ribs every 72 cm , lightweight concrete blocks of $60 \times 20 \times 25 \text{ cm}$ and compression layer 5 cm thick. Concrete type HA-25/B/16/I, of 25 N/mm^2 was used, soft consistency, maximum aggregate size of 16 mm in normal environment, manufactured at the plant (Josa, et al., 1997). The welded wire fabric measured $20 \times 30 \text{ cm}$ with a longitudinal and transverse diameter of 5 mm , using steel type B 500T.

Both models are supported by four concrete pillars located in the corners. Within the constructive logic, the vault should be supported by masonry elements, but this would not allow a homogenous comparison between both models. In Figure 1 we can see a vault supported on reinforced concrete pillars.

Figura 1. Sistema de apoyo de bóveda sobre pilares de hormigón
Figure 1. Vault system supported on concrete pillars

2.2 Evaluated Hypothesis

Two structures have been considered, a vaulted-type and a reticulated one; a simulation of existing real situations was taken as a model, intentionally avoiding working with models offered by calculation software.

For calculation purposes, the concrete structures are weighted with the safety coefficients imposed by different standards, both of factored loads and stress reduction factor for materials. The masonry structures (vaults) are analyzed with geometrical safety coefficients, instead of weighting loads and stresses, since its critical point is in geometry and not in the material's stresses.

Likewise, the foundation has been excluded from the study, since we are comparing the constructive system of two structural systems, independently of their settling on the ground. Once again, the inclusion of the foundation would alter the results for the pretended objective, since it would introduce another variable such as the location and the characteristics of the ground, an issue which is of no interest for the purpose of our analysis.

In order to carry out the vault analysis in terms of the thrust, the method of graphical statics of Karl Culmann (Jacobo, 2004) and the theories of Jacques Heyman were used.

2.3 Life Cycle Assessment

A product's life assessment is a methodology which intends to identify, quantify and characterize the different potential environmental impacts, associated to each one of the product's useful life stages (Thormark, 2002). In order to develop the present study, the Life Cycle Assessment (LCA) was used, according to the ISO 14040 and ISO 14044 standards, dividing the life of each material (Sartori and Hestnes, 2007) forming the structure into five stages:

- The manufacture, which includes the extraction of raw materials and the manufacturing process.
- The delivery of the material to the consumption point.
- The work of putting the used resources in the construction process.
- The useful life of the used resources.
- Demolition and recycling.

The work development has envisaged all environmental impacts, without distinguishing the moment and place where they have been produced, in order to avoid implementing actions tending to improve an environmental aspect while worsening another.

The stages followed in the LCA have been: definition of objectives and scope, inventory, impact assessment and results' interpretation.

A Life Cycle Inventory (LCI) has been carried out, which quantifies raw materials and energy consumptions together with the emissions to the atmosphere and all solid residues poured into the water (environmental loads) derived from all processes. In other words, each constructive product has been evaluated throughout its life cycle, with the aim of specifying the interaction of the products with the environment, thereby assessing the energy cost, CO₂ emissions, residues' generation, and the necessary labor force and economic cost of the construction (Cardim de Carvalho, 2001).

In order to determine the energy used in the construction and the environmental emissions, the price index 2011 BEDEC PR/PCT of the Instituto de Tecnología de la Construcción de Cataluña (ITeC, 2011) was used. Table 1 details the values of energy and emissions needed to produce the materials used in the development of this work.

Tabla 1. Valores energéticos y de emisiones utilizadas en el proceso de cálculo
Table 1. Energy and emission values used in the calculation process

Material	Coste energético/Energy Cost MJ/kg	Coste energético/Energy Cost kWh/kg	Emisión/Emission CO ₂ kg CO ₂ /kg	Peso específico/Specific Weight kN/m ³
Acero/Steel	35.000	9.722	2.800	78.500
Gasóleo/Gas Oil	10.100	2.806	0.003	8.900
Cemento/Cement	4.360	1.211	0.410	13.950
Cal/Lime	3.430	0.953	0.320	9.950
Ladrillo/Brick	2.321	0.645	0.180	12.070
Madera/Wood	2.100	0.583	0.060	14.600
Yeso/Gypsum	1.800	0.500	0.160	12.500
Áridos/Aggregates	0.100	0.028	0.007	15.000
Arena/Sand	0.100	0.028	0.007	15.200
Agua/Water	0.050	0.014	0.001	10.000
Escombros/Debris	-0.050	-0.014	0.000	12.500

For the products that have been manufactured with energy recuperated from materials or energy that has been disposed of as a residue (AENOR, 2006), the evaluation of the recuperated energy has been calculated according to equation 1.

$$Er = \frac{(R - E)}{(R - E) + P} \times 100 \quad (1)$$

Being Er the recuperated net energy expressed in %, P the amount of primary sources energy used in the construction process, R the amount of energy coming from the energy recuperation process and E the amount of energy of primary sources used in the energy recuperation process, all of them expressed in MJ.

In order to determine the prices and performances of the materials and labor force used in the execution process, the Base de Precios de la Construcción de Extremadura, Edition 2010, has been used (Consejería de Fomento, 2010). In the calculation of the construction's economic cost, an average cost of 13.50 €/h for skilled workers and 12.80 €/h in the case of assistants and unskilled workers.

3. Discussion and Development

The results obtained during the work development are described below in terms of the energy invested in the constructive process, the CO₂ emission, the quantity and quality of the labor force needed in the construction, the type of residues generated in the packing process and the works, and the total cost of the constructive process.

3.1 According to the energy invested in the constructive process

The energy consumed in the constructive process indicates the energy effort needed in the construction of a structure, considering the energy used in the manufacture of each of the materials used in the constructive process (Argüello Méndez, Cuchí Burgos, 2008).

The manufacturing process of the construction materials, and of the products that form them, produces an environmental impact, whose origin is in the extraction of the natural resources needed for its elaboration, including the manufacturing process and the energy use which derives in toxic emissions into the atmosphere with contaminant, corrosive and harmful results for health.

It has been demonstrated that the energy used in the constructive process of vaulted structures is lower than the necessary one to build reticulated structures, as shown in Figure 2, which illustrates the total energy use both in the material manufacturing process and the transport and construction of a reticulated structure, in relation to another made with arris vault, considering different modulations. This energy has been calculated in terms of the life cycle inventory of the products, the amount of materials forming each one of the structures and the energy values shown in Table 1.

Figura 2. Energía consumida en el proceso constructivo de distintas estructuras abovedadas respecto a reticulares en función de distintos módulos constructivos

Figure 2. Energy used in the constructive process of different vaulted structures in relation to reticulated ones, considering different constructive modules

For a 5x5 structural modulus, the process of manufacturing the necessary materials and building a vault consume 10,914MJ, while a reticulated structure would consume 48,655MJ. It is also evident that, as the interaxial distance of the slab pillars increases, the energy invested in the construction process of the vaulted structure decreases proportionally to the one needed to build a reticulated structure.

3.2 According to the CO₂ emission of the constructive process

The carbon dioxide emission to the atmosphere during the manufacturing and construction process is the variable that indicates the impact of the structure's building process on the environment, and how it contributes to increase the Planet's Global Warming Potential (García Casals, 2004).

The emission of gases into the atmosphere, measured in kilograms of equivalent CO₂ emissions, indicates the Global Warming Potential (GWP) caused by different gases emitted during the production and setting up of the construction materials which generate the greenhouse gases effect (GEI): carbon dioxide (CO₂), carbon monoxide (CO), methane (CH₄), nitrogen oxides (NO_x), ozone (O₃), sulfur dioxide (SO₂) and chlorofluorocarbons (CFC), (Intergovernmental Panel on Climate Change, 2007).

Figure 3 illustrates the carbon dioxide emission derived from the manufacturing process of materials, their transport and construction of a reticulated structure in relation to another made with arris vault, considering different modulations,

and based on the Life Cycle Inventory generated during the study's development. These emissions have been calculated in terms of the product's life cycle inventory, the amount of materials forming each one of the structures and the emission values indicated in Table 1.

Figura 3. Emisión de CO₂ en el proceso constructivo de distintas estructuras abovedadas respecto a reticulares en función de distintos módulos constructivos

Figure 3. CO₂ emission in the constructive process of different vaulted structures versus reticulated ones considering different constructive modules

It is possible to observe how the carbon dioxide emission in the manufacturing process of the materials, their transport, arrangement and manipulation in site of vaulted structures is lower than the emission produced by the construction of reticulated structures. Throughout the research we also analyzed the emission of other gases with greenhouse effect derived from the manufacturing process, transport and construction of this type of structures, such as NO_x, SO_x and CO, and they all proved to be lower in the vaulted construction hypothesis than in the use of reticulated slabs.

3.3 According to the Amount and Quality of Labor Force

Figure 4 shows the number of labor hours used, classified by skilled worker hours and assistant hours, in the building process of reticulated and vaulted structures. In order to calculate the performances of labor force, the Base de Precios de la Construcción de Extremadura (Cuadrado Rojo and Losada Rodríguez, 2007) was used, breaking down each work unit in simple units in terms of each one of the skills involved in the execution process.

Figura 4. Mano de obra necesaria en el proceso constructivo de distintas estructuras abovedadas respecto a reticulares
Figure 4. Labor force needed in the constructive process of different vaulted structures in relation to reticulated ones

It can be seen that in all analyzed assumptions the labor force needed in the constructive process of vaulted structures is higher than the one needed to build reticulated structures. It is also evident that the labor force needed to build vaulted structures has to be more qualified than for reticulated structures. A very qualified labor force reduces the execution time, while an unskilled labor force substantially increases it.

3.4 According to the Generation of Residues Derived from the Constructive Process

Figure 5 illustrates the average amount of residues generated in the construction process of the analyzed structures, expressed in kg per area unit, and classified in terms of their origin, in residues coming from the packing of different materials needed for building, such as paper bags, polyethylene, plastics in general, and residues derived from the constructive process, mainly debris and inert material rests. The residues calculation was made considering the product's life cycle inventory.

Figura 5. Cantidad media de residuos generados en estructura abovedas frente a reticulares

Figure 5. Average amount of residues generated in vaulted structures vs. reticulated ones

It can be observed how the generation of residues in vaulted structures is lower than for the construction of reticulated structures, mainly concerning the residues derived from packing, which are 177.78% lower than in the vaulted structures (Ruiz Larrea et al., 2008). Additionally, the residues derived from the constructive process are lower in the vaulted structures since part of the recycled debris coming from ceramic materials can be used for filling the spandrels of the vaulted structures, because they are inert materials.

The selective collection of residues is essential both for facilitating its valorization and to improve their handling in the dumping place (Álvarez Ude Cotera, 2003). Once classified, the residues can be sent to recycling specialized managers.

3.5 According to the construction's economic cost

The structures' execution cost is the variable indicating the economical feasibility of its utilization (Alfonso, 2003). Figure 6 illustrates the cost of the construction process (CSU), including the labor force needed for the execution, the cost of the materials and the auxiliary means used for different vaulted structures, comparing them with reticulated structures considering their modulation.

Figura 6. Precio de ejecución material de las estructuras abovedadas respecto a forjados reticulares

Figure 6. Material execution price of the vaulted structures in relation to reticulated slabs

We may observe that the construction cost of the vaulted structures is lower than the one calculated to build reticulated structures. Nevertheless, as shown in Figure 4, more labor force is needed for vaults than for reticulated slabs. The vault's lower construction price is a result of the lower price of the materials used in its construction: lime, gypsum and masonry versus cement and steel. In relation to the execution cost, the value corresponds to Spain; naturally, this datum may vary according to the execution place of the structure, basically due to the influence of the labor cost.

4. Conclusions

Although from a functional point of view both structures are equivalent, in relation to their bearing capacity, they are not homogenous in their environmental balance in quantitative terms. In order to demonstrate the results of the research, Figure 7 illustrates the variables analyzed in the development of this study: generated residues, environmental emissions, necessary labor force, execution cost, energy invested in the manufacturing process of the materials and in the constructive process, and the safety level in the execution stage of a reticulated structure versus a vaulted one, with a 6x6 modulation.

Figura 7. Comparativa entre una estructura abovedada y otra reticular de 6x6, en función de las variables analizadas en el estudio
Figure 7. Comparison between a vaulted and a reticular structure of 6x6, based on the variables analyzed in the study

As shown in Figure 7, the construction of vaulted-type structures needs more labor force; and regarding safety in the execution stage, the accident risk increases because the vault is built without formwork elements. Therefore, safety measures and monitoring have to be multiplied in this stage, especially until finishing the vault's lower layer. On the other hand, the materials forming the vault consume less energy in their manufacturing process and assembly in site, with less emission of gases with greenhouse and acidifying effect into the atmosphere.

In order to assess the total results, it would be necessary to transfer all variables to a same unit, expressing for example in euros, the consumed energy cost, labor cost, CO₂ emission cost, residues cost, and the cost of the thermal and acoustic isolation. The result of this operation will differ according to the country and place where the works are executed.

Concerning the environmental effects, it has been demonstrated that the vaulted construction fully complies the current requirements in terms of sustainability, CO₂ emissions and residues' production. Not all countries have the same regulations in this matter, and some of them penalize the negative effects on the environment more than others.

In relation to the labor force, qualification is a determinant variable in the cost of masonry structures. A very skilled labor force reduces the execution time, while an unskilled labor force shall never be capable of finishing the work.

It is evident that a greater labor force can be an advantage in a high unemployment rate scenario, economic recession periods, and in countries with cheap labor force.

As for isolation, it has been detected that vaults with filled spandrels offer a great thermal isolation in comparison to other structural systems due to the amount of mass they represent. Furthermore, the thermal isolation increases in terms of the number of layers and their thickness. Likewise, vaults offer a great acoustic isolation in comparison to other structural systems for two reasons. First, because the vault is formed by discontinuous elements that difficult the sound waves' dissemination, especially, those produced by impact. Second, due to the mass amount that is greater than in any other structural system.

For all these reasons, we may conclude that the use of vaults, as masonry structures, is advisable as long as we are not dealing with very high buildings. We can even state that this constructive technique may coexist with the cutting-edge technology of today's society, resulting in a product with high economic, functional and energy performances, and that it is possible to replace the conventional slabs by others based on vaults.

To build durable buildings, not only in terms of a technical problem but also of a design parameter that has to avoid its functional obsolescence, is a crucial matter in the construction's environmental impact. During the development of the research we detected that, from the perspective of the environmental sustainability and its execution cost, the use of vaults is more interesting when it comes to cover larger spans.

In the deconstruction stage, the residues' volume generated by a vaulted structure is greater than the one generated by a structure made of reinforced concrete, since the former fill a greater volume (CEDEX, 2010). However, recycled debris derived from ceramic materials have more use possibilities in public works and building (Cuchí and Sagra, 2007), since, among others, it can be reused as fill for spandrels, because it is considered inert material.

5. Discussion

Masonry structures are recommendable in low buildings, where thrusts can be easily conducted to the ground. Their use in skyscraper-type buildings is unthinkable. In this field they cannot compete with concrete structures, or even steel ones, but this does not turn them useless.

Their use is advisable under certain conditions, not only for environmental issues, but also for strictly economical reasons, for example in the developing countries having a large number of labor force, and at the same time a shortage of industrial production materials such as cement or steel.

No society can afford to throw away an acquired knowledge by simply arguing its usefulness. Iron and concrete technologies are not within the reach of all the planet's inhabitants, and those of us who enjoy them cannot boast of not losing them in a future which is at least uncertain. Fiction literature and cinema present us a possible future with cultural and technological setback. The oil crisis made it necessary to intensify the consumption of materials such as charcoal, and to remove the dust from old technologies like wind mills in order to take advantage of other energy sources such as the aeolic. It is possible that in the future, for unsuspected reasons, we may have to resort once more to the vaulted constructions.

Currently, the use of vaults is almost exclusively limited to ornamental aspects, intentionally eluding its structural character. In order to avoid its disadvantage position in the market in relation to the concrete structures, we should have a standard of similar characteristics to that available for materials such as concrete and steel. It is evident that vaulted structures are not included in the regulatory framework applied to building, neither new works nor reconditioning works; thus, from a legal perspective, they are in no man's land, they do not exist. It would be advisable to issue certain minimum standards that would allow their use offering a minimum guarantee both for constructors and users. For example, in Europe there are "Eurocodes" for concrete, steel, wood, etc., but there is not any that can be applied to masonry works, to vaulted structures.

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