Masonry in the seismic areas of the Americas, recent investigation and developments

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Summary

Masonry, the oldest construction method, has become one of the major competing systems in modern construction. The great interest in its use around the world is due to its metamorphosis from a brittle and fragile material to one that can successfully withstand earthquake and wind forces while maintaining those features that in the past made masonry the preferred construction material. This paper reviews in general terms, the use of reinforced masonry in the construction of bearing wall buildings. It describes the different ways used to reinforce masonry walls to withstand earthquake forces. It discusses current issues of interest and areas of research, related in particular to the seismic resistance capabilities of the system. The paper also reviews the current situation in countries located in seismic areas of the Americas, with particular emphasis in Latin American countries.

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Transformation of masonry into a structural material

Masonry construction underwent its first major transformation, since Roman times, with the introduction of reinforced concrete slabs as floor and roof systems in building construction, allowing the formation of rigid diaphragms. With proper connection between walls and diaphragm, this development permitted the distribution of horizontal load proportionally to the walls' rigidity, forcing them to work mainly under in-plane loads. Another major development was the incorporation of steel reinforcement in walls to provide them with tensile resistance. This development originated in California, after the severe damage inflicted on unreinforced masonry buildings by the 1933 Long Beach earthquake[1,2] (see Table 1).

These two developments, coupled with the accessibility to industrially produced quality-controlled masonry units with increased compression strength, enabled the construction of taller structures and the reduction in wall thickness, substantially increasing the efficiency of masonry construction.

In the last 40 years, first in the United States and Canada and later in Latin American countries, renewed interest in masonry made this material the object of extensive research to understand its behavior, define its mechanical properties and to improve its safety and seismic performance. In this process, masonry underwent a transformation from an architectural material into a true structural material, a transformation from a fragile and brittle material into one that can show outstanding ductile behavior.

Masonry use for the construction of bearing walls for buildings

Although masonry has many uses and applications, such as bearing walls, partitions, veneer walls, retaining walls, fences, sound barriers, infill walls and others, this paper focuses on the use of masonry for the construction of bearing walls in buildings.

Abbreviations

ACI = American Concrete Institute
ASCE = American Society of Civil Engineers
ASTM = American Society for Testing and Materials
FEM = finite element method
FEMA = Federal Emergency Management Agency
MSJC = Masonry Standards Joint Committee of ACI, ASCE and TMS
NEHRP = National Earthquake Hazards Reduction Program
NSF = National Science Foundation
TCCMAR = Technical Coordinating Committee for Masonry Research
TMS = The Masonry Society
UBC = Uniformed Building Code
URM = Unreinforced Masonry
US = United States of America

Table 1

Developments that enabled the transformation of the traditional masonry building construction methods:

- the incorporation of reinforced concrete slabs, allowing the formation of rigid diaphragms
- the incorporation of steel reinforcement enabling masonry walls to resist tensile stress beyond the initial cracking, and
- the development of masonry units with greater compression strength enabled the reduction in wall thickness.

Fig. 2 Confined masonry in Colombia

Fig. 3 Confined masonry in Perú

It further restricts its scope to load-bearing walls belonging to diaphragmed buildings; in other words, to walls subjected primarily to in-plane forces.

In Latin America, masonry bearing wall construction is used mainly for the construction of apartment buildings for medium- and low-income families (Figs 1–4). The usual height limit is five stories, coincidental with most construction codes' height limit without elevator, and a realistic height limit for the masonry units currently in use in Latin America. It is reported that eight-story buildings are been built in Costa Rica[3] and Venezuela[4].

In North America, reinforced masonry is mainly used for building apartments, schools, hotels and hospitals. Apartment buildings of around 20 stories have been built and a 28-story hotel in reinforced masonry has been built in Las Vegas[5].

Wall reinforcing

The way masonry walls are reinforced evolved following the availability of masonry units. In the United States, hollow core concrete units, permitted the strengthening of masonry walls with vertical and horizontal reinforcement distributed inside the wall.

Fig. 4 Confined masonry in Chile

Fig. 1 Reinforced masonry in Mexico

Masonry so reinforced is commonly called 'reinforced masonry'. Reinforced masonry is used both with blocks laid with mortar and with mortarless units. In Latin American countries, following the strong colonial tradition, masonry units were made of solid brick, tensile reinforcement was placed on the perimeter of the wall, in cast in-place concrete elements. This system of construction, is called 'confined masonry'. Confined masonry construction remains in many countries the preferred way to construct reinforced masonry. Reinforced masonry with distributed reinforcement, adapted from the

North American practice, is also widely used with different types of masonry units besides the standard concrete blocks, e.g. clay hollow blocks, hollow bricks made out of either clay, concrete or sand–lime. Partially grouted masonry with joint reinforcing is usually used. The development of industrially produced hollow brick units with a smaller width than that of the standard concrete block, followed the need to increase the usable area, made the system more efficient.

CURRENT ISSUES IN NORTH AMERICA

In the US, current developments in the masonry construction include URM retrofitting techniques, a limit-state masonry code, and improvements in material specifications and construction procedures[6]. These developments are due mainly to several, coordinated efforts. Among these are the NSF-supported TCCMAR program, the NEHRP with its FEMA 273 guide, and the recently issued limit-state masonry code, under the auspices of the MSJC.

Some of the recent investigations are reviewed in the following paragraphs:

Bond strength

Bond between masonry units and mortar continues to be a critical issue. Although quite a number of investigators are currently looking at this crucial subject it remains perhaps the most difficult subject to assess due to the many variables involved in developing bond strength. Bond depends on the quality of mortar, its components and their proportions and the mixing process, on the properties of the unit and on the masonry construction practice and procedures[7]. Wakefield[8] addresses the relationship between different types of mortar and how they must be compatible with the various kinds of masonry units and their intended use. The specification of mortar by proportions and not by its compressive strength gives the designer the ability to choose the attributes which are deemed most important[8]. After conducting experimental studies of the microstructure and mechanisms of bond in masonry, Lange[9] concludes that water transport is a dominant interaction factor for bond strength between mortar and masonry units. Several factors enhance the bond strength of mortars:

- Additon of lime[10].
- Increasing paste content in mortars overdosed with air-entraining agents[11].
- Addition of fines in sand[12].
- Inclusion of polymer additives[13,14]
- Adequate curing[15].

Suter[16] stresses the need to incorporate requirements for minimum acceptable bond strength in codes and for designers to include bond requirements in construction specifications as well as bond testing. Robinson & Street[17,18] proposed a standard test procedure for determining adhesion strength of mortar to brick and their results show less variability and better repeatability than with the ASTM E518 procedure. If these results are confirmed by further testing, their adoption would be beneficial since the development of an adequate and low-cost testing procedure is a much needed requirement. Any improvement in bond strength will undoubtedly bring benefits to the serviceability, performance and durability of masonry structures[16].

Shear strength and horizontal reinforcement

The shear strength of masonry wall continues to be the subject of extensive investigation. This is understandable because the reliability of masonry construction rests upon the reasonable prediction of its shear resistance. Recent investigations address different parameters that affect the shear resistance of walls. Brunner et al[19] study the effect of low aspect ratio of reinforced masonry shear walls on the strength and failure mechanism and propose an analytical method to estimate both the flexural and shear capacities of shear walls of any aspect ratio. Although the analytical procedures proposed by them are cumbersome for the design office and should be simplified, the analysis of the problem is very clear and illustrative of its complexities. Provision of horizontal reinforcement is in the essence of seismic resistance in the design of reinforced masonry walls, and codes stipulate minimum horizontal steel ratios. However, as expressed by Schultz[20], 'the historical development of these limits has been based on the control of cracking due to volume changes, rather than on the behavior of masonry walls subjected to lateral loads'. Based on investigations carried out by Shing et al[21–23], Schultz proposes expressions for horizontal steel ratios for code that meet both the strength and energy criteria and considers the ratio of the nominal thickness of masonry to its effective thickness which takes into consideration partially grouted walls.

Ibrahim & Suter[28] propose expressions for the shear resistance of horizontal steel (V_s) and for the residual strength of masonry (V_m).

Partially grouted masonry

Shultz's work[24] suggests that partially grouted masonry is a viable lateral load-resisting system for seismic conditions and that bed joint reinforcing can be effective, provided that it meets the minimum requirements regarding tensile behavior. Shing & Cao[25] find the behavior of a partially grouted reinforced masonry wall very similar to that of a reinforced concrete infilled frame. Partially grouted masonry could provide the required seismic resistance to one- or two-story buildings certainly at a lower cost than fully grouted masonry. However, it is important to note that partially grouted masonry has internal discontinuities that cause stress concentrations which could reduce its seismic performance. In fact, one of the causes of failure of reinforced masonry buildings in the 1985 Chilean earthquake[26] was the use of partially grouted masonry.

Wall behavior

As a part of a larger study to investigate the behavior of reinforced masonry for the development of limit state design criteria, Atkinson et al[27] conducted an experimental research program to look into the tension stiffening behavior of reinforced masonry. The study focused on the stress–strain response prior to yield and after yield and on the effect of steel ratio on ductility. Tensile behavior of reinforced masonry after reinforcing steel yields was shown to be highly dependant on the steel ratio, with small values of the steel ratio associated with large losses in overall tensile ductility. These studies will contribute to a better understanding of the behavior of masonry walls under tension and to the establishment of the lower limit for tensile reinforcement. Experimental studies conducted by Ibrahim & Suter[28], on five masonry shear walls tested under cyclic loading to study the softening behavior and ductility of the cracked walls undergoing brittle shear-dominated progressive failure, showed clear evidence that reinforced masonry walls with low aspect ratios, exhibit significant ductility and energy dissipation capability when subjected to cyclic displacement reversals. Hamid & Celtikci[29] studied the effect of flexural cracking on lateral load distribution and confirmed that cracking may cause redistribution of loading and higher inter-story drifts. They recommended that cracking should be investigated in a design problem, especially when there are unreinforced masonry walls. El-Shafie et al[30] present a literature review on reinforced masonry walls with openings and discuss various issues regarding the behavior, analysis and design of this type of walls and in a recent study[31] proposed a model for prediction of postcracking stiffness of reinforced masonry shear walls with openings.

Prestressed masonry

Prestressed masonry has been used in several applications of new construction and repair in Europe with a few examples in the United States. Prestressed masonry construction has been shown to be cost competitive with reinforced concrete and masonry construction[33,34]. Prestressed masonry walls can enhance the serviceability, ultimate strength, and ductility of hollow masonry walls[32]. This statement has proved to be valid in many investigations as well as real applications for out-of-plane loads. The application of post-tensioning forces to walls that will be subjected to both vertical and horizontal in-plane loads, is another matter. Although there is no doubt that masonry wall serviceability could improve enormously due to prestressing, there are many questions that need to be answered as yet regarding a wall over all behavior under severe seismic loads (e.g. vertical and diagonal compression resistance, ductility and energy absorption, reparability, etc.), meanwhile the MSJC code treats prestressed masonry for seismic purpose, as though the masonry is nonductile, similar to unreinforced masonry[35].

Analytical models and engineering models

There has been a substantial effort to develop practical and cost-effective analytical tools based on numerical methods, specifically the finite-element method, to solve engineering problems in masonry[25, 36–42]. As masonry is a composite material, whose behavior is anisotropic, this task has been difficult. Saliba et al[36] compared two different models for analyzing masonry structures: the two-material model where both brick and masonry are assumed to be isotropic, and the equivalent-material model, where the anisotropic properties are represented by four elastic constants for the two-dimensional wall. While the former model limits its applicability to static loads and linear elastic behavior, the latter model can handle dynamic loads and is capable of predicting both the elastic and inelastic behavior of any wall including openings. However, these models are out of reach for a design office as they require large and fast computers involving high costs. These methods could be very useful in the near future, once significant advances in computer technology could make it possible for engineers to run these models on work stations[36]. To assess the capability of finite element models in predicting wall behavior, Shing & Cao[25] model partially grouted reinforced masonry shear walls which were previously tested by Shultz at the National Institute of Standards and Technology. Although there are some discrepancies between the numerical values and test results, the FEM modeling proves to be a formidable tool to analyze complex anisotropic and nonhomogeneous systems such as a masonry wall. Zorapapel et al[37] utilized Monte Carlo simulation to assess the performance of concrete masonry structures in an attempt to define and quantify probabilistic performance measures for concrete masonry wall structures at both the element and system levels, as well as to explore the interrelation between system ductility and redundancy. They studied both balanced and unbalanced wall systems and concluded that system robustness, measured by the system ductility index, increases with the number of walls. The low robustness provided by unbalanced systems requires special attention in designing these structures. The information that can be obtained with this type of analysis will be very useful at the design stage to select an appropriate wall configuration.

Materials

There is increasing interest in North America on the use of waste materials in the manufacture of bricks and concrete blocks, both as a practical and economical way for waste disposal and as a beneficial additive in the manufacture of masonry units. The increasing awareness on environmental issues and increasingly stringent environmental regulations will bring in the near future an extensive use of waste material in brick manufacturing. Ramadan et al[43] report on the use of waste in the fabrication of bricks, whereas Gawedzinski & Richardson[44] report on a testing program to determine the effectiveness of adding granulated thermoplastic to concrete masonry in order to improve its thermal insulating properties while maintaining its structural strength. In some Latin American countries, e.g. Peru, where bricks are manufactured using clay material taken from very scarce agricultural land, the use of waste materials could slow down the loss of arable land.

Masonry properties

Khalaf & Naysmith[45] propose the use of a simpler test specimen for an evaluation of the shear strength of masonry bed joints. The proposed single-shear test is an easier and less expensive method which gives consistent results and apparently reduces the variability characteristics generally inherent in standard shear tests. An experimental investigation of masonry blocks compressed in two orthogonal directions proposed by Khalaf[46] could prove useful for the evaluation of partially grouted shear walls under diagonal compression.

For the development of the limit states MSJC design code for masonry, several investigators have worked to establish design parameters. Hamid[47] has performed an evaluation of the test data from the US–Japan Coordinated Program on Masonry Building Research to compare key design parameters such as compressive strength, strain at peak stress, and modulus of elasticity for both concrete and clay masonry. The study shows that masonry is not a generic material; in fact, grouted concrete and clay masonry exhibited somewhat different behavior under concentric and eccentric loading.

CURRENT ISSUES IN LATIN-AMERICA

Despite strong competition from different construction systems for apartment buildings, in particular those created by the introduction of modular steel forming systems for concrete wall construction; masonry remains the preferred construction material for housing throughout Latin America.

In many Latin American countries, a large proportion of housing is nonengineered construction carried out by home owners in shanty towns (or marginal areas in large cities) without regard to codes. This informal construction imitates designs from the engineered construction in the formal sectors of the cities. However, the resulting construction is not always safe as frequently copies are unacceptable extrapolations of the standard practice.

Regulations limit the height of masonry buildings to five stories (15 m in Peru); however, buildings of up to eight stories have been reportedly built in Caracas, Venezuela[4]. Confined masonry is the preferred construction system. Its main advantage is that it can be constructed with a variety of units and does not require qualified labor.

Reinforced masonry

Reinforced masonry in Latin America is an adaptation from US practice. Some countries have adopted entirely US codes and standards. Others, like Chile[26] and Peru[48], have adapted US practice to their own conditions. The adaptation process has not always been successful and many buildings have had earthquake-related problems[24,49]. When reinforced masonry was built according to US standards, its behavior has been excellent[50]. In some countries like Costa Rica, reinforced masonry is the preferred construction system[3]. On the other hand, due to the fact that reinforced masonry requires industrially produced special masonry units, qualified masons and close supervision, its use has been rather limited in most of the other countries. A recent investigation in Peru[52] on reinforced masonry walls with calcium-silicate units has concluded that toe confinement of masonry walls provided with steel plates in horizontal joints substantially increases tolerable angular distortions as well as lateral load resistance. The investigation has also shown that continuous vertical reinforcement substantially improves the wall performance in the inelastic range.

Confined masonry

Confined masonry is a composite construction system which still poses many questions that need answers relating to its behavior under dynamic lateral forces. One main issue is its tendency to form a fragile mechanism or a soft story at the ground-floor level, after the masonry panel has deteriorated[53, 54]. Flores & Alcocer[55] demonstrated in recent tests that the largest damage in a three-story structure without horizontal reinforcement was concentrated at the ground-floor level. Moroni et al[56], report on analytical investigations carried out on actual three- and four-story buildings constructed mainly with confined masonry walls subjected to displacement demands of 0.2–0.6 cm. The prevailing failure mechanism, when shear behaviour controls the response, corresponds to a first soft story. This phenomenon coincides with the observations made during earthquake surveys. Much effort has been expended in investigating this problem and the ways to solve it. One way that has proved to be very efficient is to provide horizontal reinforcement in the walls[54,55,57,58]. Aguilar et al[59] found that specimens reinforced horizontally with deformed cold-drawn wires showed a considerably improved behavior under alternating cyclic lateral loads. In addition, these specimen showed a more uniform distribution of inclined cracking compared to the unreinforced control structures. Alcocer et al[54] found that only the heavily horizontally reinforced specimen failed due to shear-compression distress in the masonry panel. Brittle failure was observed in all walls when the brick webs failed and the face shells fell outwards. The effectiveness of horizontal reinforcement depends on the reinforcement ratio. It is proposed that the horizontal reinforcement ratio should be between 0.0005 and 0.0015. The maximum amount is intended to avoid wall crushing at drifts up to 0.01. Due to the brittle mode of failure, a maximum drift ratio of horizontally reinforced confined masonry walls is recommended as 0.006.

Alcocer & Zepeda[60] report on the behavior of four large-scale isolated confined load-bearing walls tested under constant vertical axial load and cyclic lateral loads. Results of tests indicated that multi-perforated clay bricks could be used for earthquake resistance if a minimum amount of bed reinforcement and proper tie-column detailing are provided; recommendations are made on the force reduction factors to be used, calculation of the nominal lateral strength of walls reinforced horizontally, limits on the amount of horizontal reinforcement, detailing of confined walls and for the design of medium-rise buidlings; preliminary material tests indicated that the masonry shear strength strongly depends on the amount and uniformity of the mortar penetration into the brick cells, which in turn is a function of mortar fluidity. In a recent investigation, Lafuente et al[4] question the validity of 'taking advantage of the inelastic behavior of the material for seismic resistance design and suggest exploration of other alternatives to obtain ductile mechanisms which allow stable energy dissipating histeresis cycles'. The questioning is valid for the characteristics of the confined masonry walls that were tested, namely walls built with nongrouted hollow units. This type of masonry, which has been widely used for engineered one- and two-story buildings, and without restrictions of height in nonengineered housing in the marginal areas of cities, should be discouraged for one- and two-story buildings, and banned for taller buildings due to its fragile behavior. It is interesting to add that the lack of ductility arises from diagonal compression failure of the masonry panel. To help in the evaluation of diagonal compression resistance of block masonry, tests of prisms under axial load parallel to the bed joint, as proposed by Khalaf[46], certainly provides a better approximation. Test results confirm in all cases that the addition of horizontal reinforcement in confined masonry walls gives the following benefits:

- Substantial increase in strength and deformation capacity after initial cracking.
- A more uniform distribution of inclined cracking
- More energy dissipation than those achieved with no reinforcement

In Latin America there is also an increasing trend to use analytical tools to model masonry to study wall behavior[61, 63]. In addition, there are many issues concerning behavior of confined masonry that need further study:

- Influence of the type of masonry unit[54]. In particular, the effect of the core size on the compression strength of a masonry panel and thus the ductility of the system. Producers of masonry units tend to increase the amount of core area over the 25% usual code limit to save material, and in the case of clay units to improve its burning uniformity. The proposed Peruvian code allows a core area of 30%[65].
- Properties of confining elements in relation to the masonry properties, i.e. what should be the ratio of f_c' to f_m'?. Should a large ratio be preferred rather than a small one? What should be the limit for the lateral stiffness of the reinforced concrete confining elements?
- Types of horizontal reinforcement. Joint reinforcement vs bond beams. Joint reinforcing used in hollow blocks of concrete or clay could lead to corrosion problems and diminished bonding when the blocks shell are too thin. Comparison of concentrated horizontal reinforcement vs distributed horizontal reinforcement. Type and amount of reinforcement at the toe of a wall to avoid premature compression failures.
- Ratio of horizontal to vertical reinforcement, with appropriate lower and upper limits.

Damage control

One major concern has been to develop crack-free walls in service conditions and walls with controlled damage in the event of a strong earthquake. Damage control, achieved by controlling angular deformation in walls, is an essential part of the design practice in Latin American countries to ensure reparability of masonry walls and thus limiting the economic loss for apartment owners. Lateral deformation of walls is usually limited to between 1/300 and 1/200.

RETROFITTING

One major concern for the engineering communities in the Americas is the existence of a large number of unreinforced masonry buildings, in both the private and public sectors and their susceptibility to the potential loss of life and of property. Thus, the strengthening of URM is the subject of extensive research to find practical, economical and effective ways of reinforcing these buildings[64]. The usual practice to reinforce URM walls in Latin American countries has been to incorporate confining reinforced concrete vertical elements in these walls, or to replace the major walls with reinforced concrete walls. Both methods are traumatic and costly. Alcocer et al[65] report on tests performed on confined wall specimens reinforced with an exterior cover steel mesh and mortar. They find the technique very effective in improving the earthquake-resistant characteristics of these walls. These jacketed walls dissipated more energy when compared with both the original and control structures. The test results suggest that this solution could be more practical, less costly and more effective than adding wall confinement.

Much effort has been expended in the US to develop less traumatic exterior reinforcing procedures, that do not introduce new structural elements in the building. Recent guidelines for rehabilitation of existing structures (FEMA 273) prescribe methods of analysis for masonry structures and strengthening procedures. Abrams & Dempster[66] discuss the merits and limitations of these methods based on experimental research. In a case study based on FEMA 273, related to seismic rehabilitation of unreinforced masonry buildings, Abrams[62] shows how enhanced performance can be obtained by increasing the inelastic deformation capacity rather than the lateral strength. Ehsani et al[67] present very interesting results of tests made on walls reinforced with fiber composites. Test results indicate that retrofitting of URM structures with composite fabrics is a very effective technique for increasing the flexural and shear strength and ductility of these elements.

Boothby[68] makes an interesting contribution towards an evaluation of the safety of older masonry structures on the basis of the properties of materials used in their construction, in particular sand–lime mortar.

Paquette and Bruneau[69] report on an analytical and experimental research currently under way to investigate the seismic resistance of unreinforced brick masonry buildings. Partial results of this study demonstrate the dominant role of flexible diaphragms on structural response.

CODES AND STANDARDS

Development of codes and standards for masonry construction was not a priority in Latin American countries until masonry started to be reevaluated some 25 years ago. Most masonry codes, as is the case with reinforced concrete and other structural materials, are adaptations of existing codes in the United States, mostly UBC[70]. Peru's current code (1977)[71] is based on working stress and empirical design recommendations. Admissible stresses in this code are based on results of an extensive test program performed on materials; i.e., units, mortars, and specimens, to determine basic design parameters. There is a committee working on a new code for the reinforced and confined masonry construction, including capacity design, ultimate strength, ductility and damage control criteria[72]. Chile's code for reinforced masonry[73] dates back to 1986 and for confined masonry[74] to 1993; their design provisions are of the allowable stress design but some concepts of the strength design have also been included[26]. Design of reinforced concrete block masonry in this code is similar to that in UBC, but a special verification of the shear strength of hollow clay brick masonry to prevent cracking under moderate earthquakes is required.

In 1987, after the Mexico City earthquake, masonry regulations were updated with the Technical Norms for Design and Construction of Masonry[75]. Mexican design provisions are based on a limit state concept, in which the external loads, modified by load factors, are compared against member strength modified by reduction factors[49].

In Colombia, the 1984 code[76] included for the first time a chapter on masonry. Masonry design provisions are based on working stresses and empirical design recommendations. Reinforced masonry codes closely follow UBC[50]. The reader is encouraged to follow discussion of regulations for seismic resistance and design in Ref.[51] In the United States a new code and specifications for masonry structures have been published in 1999 under the joint effort of ACI, ASCE and TMS[77]. The code covers the analysis and design, both for strength and serviceability, and construction of masonry structures and for the first time includes a chapter on prestressed masonry.

In Canada, the Code for the Design and Construction of Masonry Buildings is regulated by the Canadian Standard Association[78].

Closing remarks

Masonry will continue to be the most important construction material for buildings, schools and other structures in the 21st century. Significant advances in masonry construction have been made during the past 40 years in the Americas. On the other hand, in the opinion of this writer, the research and development efforts in Latin America have not been well coordinated, thus leading to duplication and waste. To avoid this, a collaborative and concerted effort should be made in the Central and South America with the participation of academia, industry and practicing engineers.

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