A shaking table pad made of Kevlar fiber-reinforced polymers

Une planche d'une table de vibration fabriquée en polymères renforcés en fibre de Kevlar

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ABSTRACT

The use of fiber reinforced polymers has been rapidly expanding to almost all engineering branches. Historically, aerospace engineering has used composite materials to solve their specific needs. Composites have also been used extensively in automobile industry, sport goods mechanical engineering, defense industry etc. In the past few decades, composite materials have found application into other engineering areas like structural engineering. Nowadays the use of composite materials in civil engineering has been explored extensively by many researchers. However, composite materials are still not commonly used in geotechnical engineering. This paper deals with that aspect and proposes the potential use of composites in some geotechnical problems. To this end, an experimental investigation was carried out to find static and dynamic properties of an in-house Kevlar fiber-reinforced polymer (KFRP). The KFRP specimens used in the experimental program were formed in the laboratory using easy-to-get commercial components, with inexpensive techniques. It should be stressed that the components used were relatively cheap as compared to those commonly used in the composites industry. Composite materials are still very expensive to build, especially when very sophisticated techniques are used to build them. The components used in this research were chosen such that they gave the best cost-benefit relation from the available choices in the non-specialized market. The specimens were conformed by wet lay-up technique and were cured in a vacuum bag in the laboratory under room temperature conditions. Kevlar fiber was used because it is easy to get from any DuPont distributor worldwide, and because its price is competitive with other high-performance fibers like carbon fibers. Also, Aramid fibers (like Kevlar) have very light weight and high tension strength as compared to fiber glass, which is very popular in the composites market. The laboratory program carried out included bending tests, free vibration tests and cycling loading. Global properties were back-calculated from these tests. Also, a strength-of-materials model was used to compute the composite's properties and its results agreed well with laboratory results. Static laboratory tests were simulated in a finite element model to corroborate experimental and analytical results. Finally, numerical simulations of the use of the advanced KFRP were carried out to show its potential use in geotechnical testing applications.

RÉSUMÉ

L'utilisation des polymères renforcés en fibre a rapidement augmenté dans presque tous les génies. Historiquement, le génie aérospatial a employé les matériaux composites pour résoudre leurs besoins spécifiques. Des matériaux composites ont été également employés énormément dans l'industrie automobile, les outils de sport, le génie mécanique et l'industrie de défense, etc. Dans les dernières décennies, les matériaux composites ont trouvé l'application dans d'autres secteurs comme le génie structurel. De nos jours l'utilisation des matériaux composites dans le génie civil a été explorée intensivement par beaucoup de chercheurs. Cependant, les matières composites ne sont toujours pas utilisées communément dans la technologie géotechnique. Ce document traite cet aspect et propose l'utilisation potentielle des composites dans quelques problèmes géotechniques. À cet effet, une recherche expérimentale a été effectuée pour trouver les propriétés statiques et dynamiques d'un polymère commercial renforcé en fibre de Kevlar (KFRP). Les spécimens de KFRP utilisés dans les recherches expérimentales ont été faits dans le laboratoire utilisant des matériaux commerciaux faciles à obtenir et des techniques peu coûteuses. Les composants utilisés étaient relativement bon marché par rapport à ceux utilisés généralement dans l'industrie de composites. Les matières composites sont toujours très chères à utiliser, particulièrement quand des techniques très sophistiquées sont employées pour les établir. Les composites utilisés dans cette recherche ont été choisis en faisant une analyse de rentabilité tels qu'ils ont donné la meilleure relation coût-rendements parmi les choix disponibles sur le marché non spécialisé. Les spécimens ont été conformés par technique de disposition humide et ont été traités dans un sac de vide dans le laboratoire dans des conditions de température ambiant. La fibre de Kevlar a été employée parce qu'il est facile d'obtenir de n'importe quel distributeur de Dupont, et parce que son prix est concurrentiel avec d'autres fibres à rendement élevé comme des fibres de carbone. En outre, les fibres d'Aramide (comme le Kevlar) sont très légères et ont une force de tension très élevée par rapport à la fibre de verre, qui est très populaire sur le marché de composites. Le programme de laboratoire a inclut les essais de pliage, les essais de vibration libre et ceux de charge périodique. Des propriétés globales ont été calculées en arrière à partir de ces essais. En outre, un modèle de résistance des matériaux a été employé pour calculer les propriétés du composite, ces résultats ont été conformes aux résultats obtenus au laboratoire. Des essais statiques au laboratoire ont été simulés dans un modèle d'élément fini pour soutenir les résultats expérimentaux et analytiques. En conclusion, des simulations numériques de l'utilisation du KFRP ont été effectuées pour montrer son utilisation potentielle dans des applications orientées à des essais géotechniques.

Keywords :Composite materials, Kevlar, Shaking table, Geotechnical engineering

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1 INTRODUCTION

Traditional construction materials like concrete, steel, wood, reinforced concrete, etc., have provided to the society with cost-effective, easy to construct structures along time. However, infrastructure built on traditional materials undergoes aging and deteriorates substantially in aggressive environments. This is true for reinforced concrete structures, where steel corrosion affects their performance, and concrete degradation contributes to this problem as well. Aged and deteriorated infrastructure is a global problem, as in almost all countries in the world there exists bridges or other structures needing strengthening, rehabilitation or replacement (Banthia, 2003). This has motivated the study of fiber-reinforced polymers (FRP) as a potential solution to the problems of steel corrosion and concrete degradation (Sakr *et. al.*, 2007). Furthermore, the need to improve not only durability but to reduce site labor cost, time and to improve safety is motivating the interest in the use of FRP materials in the construction market (Hollaway and Head, 2000).

FRP materials have been increasingly used in structural engineering. However, in other areas of civil engineering, like geotechnical engineering, this still is a very incipient subject. Accordingly, only a few applications of FRP materials have been developed in this area. However, due to their durability, customized mechanical properties and low weight, they are potential candidates to be used in geotechnical applications. Some of these may include light-weight sheet piles, easy-to-install raft foundations, pile foundations (Skar *et. al.*, 2007) and so forth. An application to geotechnical laboratory testing is presented in this paper. The application deals with the design and construction of a shaking table pad for the geotechnical laboratory of the Institute of Engineering, UNAM. A Kevlar FRP material (KFRP) was developed specifically for this purpose. To this end, an experimental investigation was carried out to find static and dynamic properties of the material. The experimental program carried out included bending and cycling loading tests. Global properties were back-calculated from these tests. Also, a strength-of-materials model was used to compute the composite's properties and its results agreed well with laboratory results. Static laboratory tests were simulated in a finite element model to corroborate experimental and analytical results. Also, numerical simulations were performed to investigate the performance of the KFRP material for the intended application.

2 KFRP USE IN GEOTECHNICAL TESTING APPARATUS

A hydraulic shaking table is to be constructed in the geotechnical laboratory of the Institute of Engineering, UNAM.

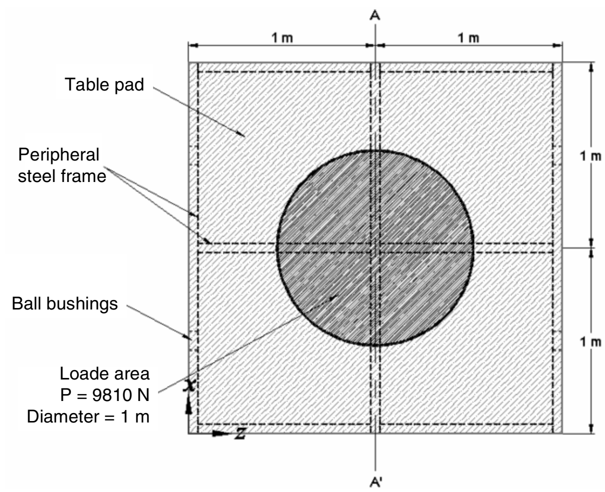

Figure 1. Shaking table pad to be built from KFRP

The apparatus will use an existing hydraulic pump, thus its design should be adapted to the pump's capabilities. The maximum load to be moved by the hydraulic actuator is 9810 N, including the shaking table pad. Therefore, to maximize the weight of the models to be tested, the pad's weight must be the minimum possible. Also, the pad has to be stiff enough to avoid excessive deflections during table operation. Figure 1 shows the geometrical description of the shaking table pad.

3 COMPOSITE MATERIAL USED

The requirements of low weight and high bending stiffness can easily be met by FRP materials. Accordingly, a Kevlar FRP material (KFRP) was developed to build the shaking table pad. The material was formed with a plywood core reinforced with Kevlar fabric in an epoxy resin matrix. The Kevlar fabric was model 745, which has Kevlar 129 fibers in two normal directions, thus making it orthotropic. The denier of the fibers was 3000. Figure 2 depicts the geometrical disposition of the FRP material, and table 1 presents some properties of each of the constituents used.

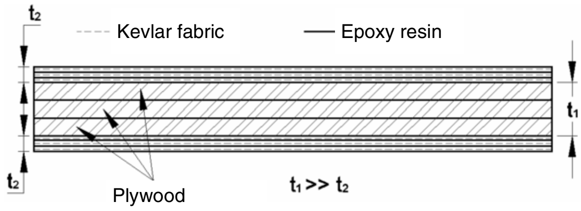

Figure 2. Configuration of KFRP used

The material was built using the wet lay-up technique (Cripps, 2000). This technique consists in forming the laminate by hand using brushes to soak the core and reinforcing fibers with the bonding resin. Once formed, the laminate is enclosed in a vacuum bag to apply a uniform pressure as the resin curing process takes place. Once cured, the bag is removed and the laminate is ready to use.

Material	E (GPa)	ρ (kg/m^3)
Kevlar fabric	100	1445
Plywood	4	530
Epoxy resin	3	1160

Table 1. Material properties of KFRP constituents

4 KFRP MATERIAL CHARACTERIZATION

Laminate beams of the KFRP material were built to test them under static and dynamic bending. The number of Kevlar layers was varied to find the optimum amount to be used in the construction of the pad. This was achieved through static bending tests, where global mechanical properties were computed from experimental results. Dynamic tests were performed to find the material fatigue. Figure 3 depicts the experimental configuration of the bending tests carried out under both static and dynamic loading. All the beam specimens had the same dimensions.

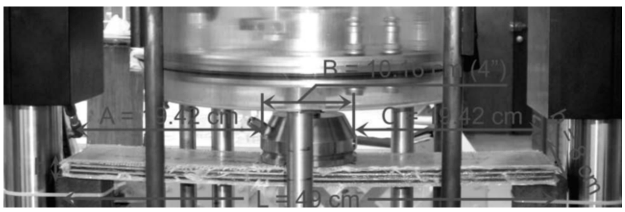

Figure 3. Experimental set up for bending tests

4.1 *Static bending tests*

All static bending tests were carried out at a deflection rate of 2 mm/min. The material responds in an elastic – plastic manner, as shown in figure 4 where a typical load (P) *versus* normalized deflection (y/h) curve is shown. The ultimate load of the specimens (P_U) was taken as the load producing a deflection equal to the beam's depth (y/h = 1). Also, the global Young modulus was computed in the 20 – 40 % range of the y/h relation, as seen in figure 4, because the material behaved elastically in this region. The global Young modulus was computed through classical beam theory. The values obtained this way compared well with those computed under micromechanics considerations (Hyer and Waas, 2000).

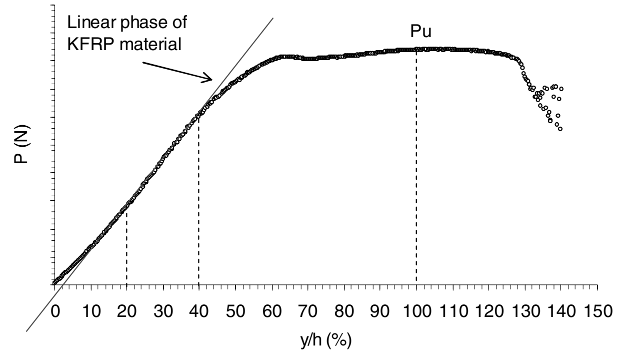

Figure 4. Typical load – normalized deflection curves for the KFRP

Tests were carried out varying the number of Kevlar layers on each specimen. Results are presented in figure 5 in terms of Young modulus normalized to material density (specific modulus). It is seen that after 3 layers of Kevlar, specific density tends to a constant value. Consequently, it was decided to use 3 layers of Kevlar (on each side of the pad) to build the final shaking table pad. The global Young modulus for this case was 15.75 GPa.

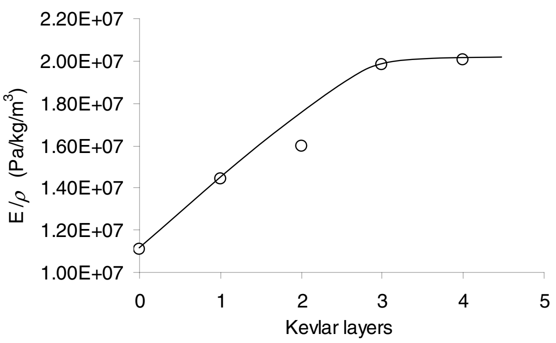

Figure 5. Specific modulus versus number of Kevlar layers

4.2 *Dynamic bending tests*

These tests were performed to investigate the fatigue of the KFRP material under cyclic loading. All tests were performed under controlled load conditions with a frequency of 2 Hz. The input loading signal was assigned a pre-load, P_0, to ensure a permanent contact between the beam specimen and the load-applying device. The pre-load increased every 5000 cycles, until failure was reached. Load amplitude was kept constant at $P_U/6$. Figure 6 depicts the typical loading conditions for dynamic testing. Results are presented only for the three layers of Kevlar configuration, because this was the case selected for designing the shaking table pad.

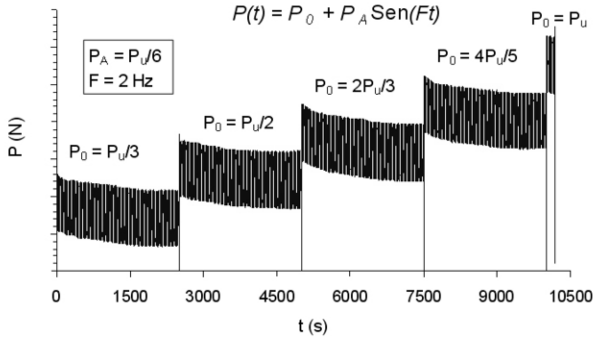

Figure 6. Typical loading scheme of dynamic bending tests

Figure 7 shows that the material exhibits a moderate hysteretic behavior, except at very high loading values where the hysteresis loops increase their area significantly until failure is reached. It is also observed in figure 7 that despite its moderate hysteretic behavior, the material practically does not degrade under cyclic loading before failure, as the slope of the load – deflection curve remains constant for each test. This demonstrates the suitability of using this material for severe dynamic loading conditions.

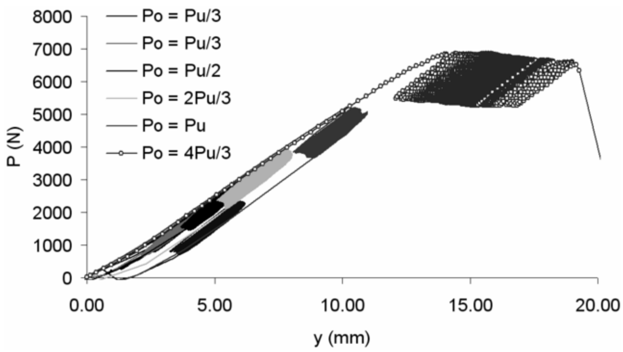

Figure 7. Dynamic load – deflection curves

5 NUMERICAL SIMULATIONS OF THE KFRP BEHAVIOR

To corroborate the global properties of the KFRP material obtained from experimental tests, numerical simulations of static bending tests were performed. These tests were simulated using finite element models. Figure 8 depicts the model used for the simulations, which consisted in 56 shell elements and 75 nodes. The shell elements were formulated using Kircchoff hypotheses. The material was considered homogeneous and linearly elastic, consistent with the beam theory used to back calculate the Young modulus from laboratory tests. Figure 9 shows the comparison between measured and computed load – deflection curves. It is seen that numerical results match very well the experimental curve in its linear portion. This means that the global properties estimated from the experimental results are adequate to represent the bending problem.

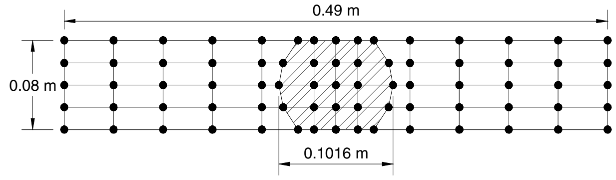

Figure 8. Finite element model used for numerical simulations

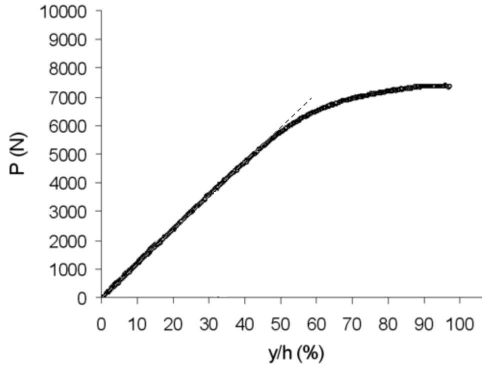

Figure 9. Comparison between measured and computed P – y curves

6 NUMERICAL PREDICTIONS OF THE SHAKING TABLE KFRP PAD

Once the properties of the KFRP material were estimated and validated, numerical simulations of the shaking table pad were carried out to investigate its behavior under service load. As shown in figure 1, the pad will rest on a peripheral steel frame. Accordingly, the numerical model (shown in figure 10) considered 40 beam elements to model the steel frame and 67 shell elements to simulate the pad. The round area shown in figure 10 is the zone where the uniform load was applied (9810 N). The steel frame will consist of a 2” x 2” x 1/8” hollow structural section.

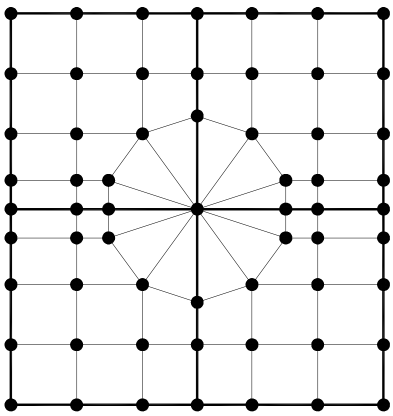

Figure 10. Finite element model of the shaking table pad

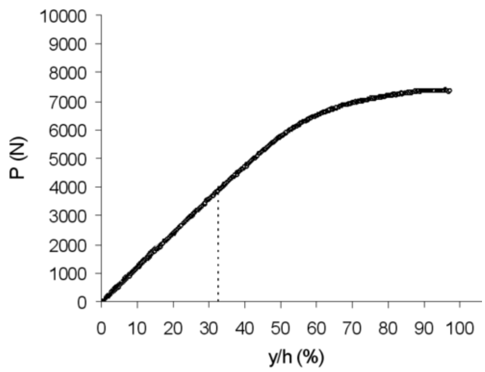

Figure 11. Load – deflection curve for a 3 Kevlar – layers beam

Since the problem is bi-dimensional, the anisotropy of the plywood will influence the KFRP bending response. This was accounted for by computing the mechanical properties of the KFRP material in the plywood’s transverse direction. The modulus for transverse direction was 11.57 GPa, and in the other direction was 15.75 GPa. As the material was considered homogeneous, deflection estimates were computed independently for each direction. The average deflection was estimated as 7.44 mm, which corresponds to a y/h relation of about 33 %. This percentage corresponds to the linear portion of the load – deflection curve shown in figure 11 for a 3 Kevlar – layers beam tested in the laboratory. As seen in figure 11, the deflection induced in the shaking table pad lies within tolerable values inside the linear range of the KFRP material.

Using the numerical model shown in figure 10, simulations were performed to investigate the mass variation of the shaking table pad if it were built from steel or aluminum. There results were compared to KFRP and are shown in figure 12. It can be observed in that figure that for the same y/h relation, the KFRP pad has the least mass with respect to the aluminum or steel pads. This strongly supports the use of KFRP material to build the shaking table pad.

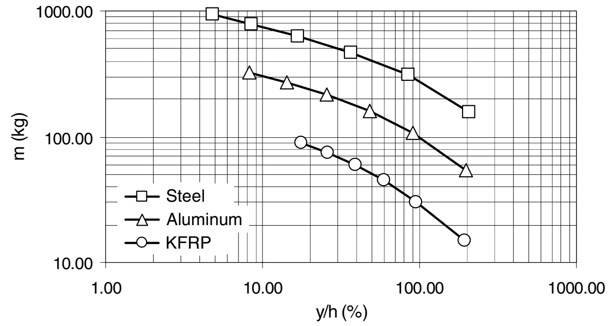

Figure 12. Mass variation of shaking table pad for three different materials

7 CONCLUSIONS

Fiber reinforced polymer (FRP) materials are being used increasingly in civil engineering. However, their use in geotechnical engineering is still very incipient. It has been shown here in this paper that these materials have a great potential that should be used to improve geotechnical engineering practice. The durability and customized engineering properties of these materials make them a feasible choice for geotechnical design. The application of a Kevlar fiber reinforced polymer (KFRP) to the design of a shaking table pad intended to be used for geotechnical testing has been presented. From the results obtained in this research, it can be said that composite materials have many advantages over traditional building materials, specially metals, since FRP have more durability and higher specific properties. Research on this area should focus on the durability of FRP materials under geotechnical environments, to make estimates of their long term behavior.

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