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Short communication

State of the practice of FRP composites in highway bridges

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ABSTRACT

This case study presents the use of fiber reinforced polymer (FRP) composites in highway infrastructure. The state of current practice of FRP materials is established through a survey questionnaire and follow-up interviews with 46 responding transportation jurisdictions in North America (44 United States Departments of Transportation and 2 Canadian agencies) to identify current challenges requiring technical and administrative efforts to facilitate the employment of this promising construction material. FRP composites for infrastructure projects are generally satisfactory and promising. Most agencies have used FRP since 1996, although some agencies reveal pioneering endeavors in the early 1990s. The nature of construction projects determines whether FRP applications are experimental or a standard practice. The survey shows that CFRP-strengthening for upgrading bridge piers (primarily columns) is the most accepted standard practice, followed by GFRP-reinforced bridge decks. Challenges experienced by the responding agencies are detailed and analyzed. Various tests at material and structure levels are conducted to examine the performance of structural members constructed with FRP composites. Despite these endeavors, the long-term durability of in-situ FRP still requires additional research to generate technical data and to convince end-users. Lessons learned from sites are elaborated to assist practitioners who are interested in FRP-based projects. The majority of respondents state that more training is necessary to help understand the use of FRP composites in construction projects.

1. Introduction

The sustainability of highway infrastructure is one of the most crucial research/practice needs in the United States. Constructed facilities deteriorate owing to physical and environmental factors, and may become structurally deficient. There are a number of contributors to such deterioration; for example, water, ultraviolet radiations, temperature, freeze-thaw, traffic load, impact, and chemicals. Accordingly, structural members do not meet their expected design life. The load-bearing capacity of these members may decrease as their physical properties change, leading to public safety concerns. The members' durability performance is also affected by the degree of deterioration (e.g., steel reinforcing bars become vulnerable to corrosion, when concrete surrounding the bars cracks or spalls). Transportation agencies are eager for alternative construction materials, which will enable them to extend the longevity of existing structural members in an economical manner.

Fiber reinforced polymer (FRP) composites are a promising material and have shown excellent performance with numerous advantages. Examples involve favorable strength-to-weight ratio, noncorrosiveness, reasonable labor, rapid execution, and reduced long-term maintenance costs [2,3]. The application range of FRP materials is broad from internal reinforcing to external strengthening [7,10,9,4]. Various FRP materials and types (e.g., sheets, laminates, structural shapes, bars, and tendons) are available for highway infrastructure [1]. Further details on the various aspects of FRP applications (e.g., durability, statistical characteristics, test methods, and long-term performance) are expounded in state-of-the-art papers [8,5,6].

Although significant advancements have been made over the last two decades from research standpoints, FRP composites have not been widely adopted by state departments of transportation (DOT), including the Ministry of Transportation in Canadian Provinces, because of their high material costs, a lack of design guidelines or specifications, procurement, and relatively short application history. The FRP community is not properly informed of the contents related to the following questions: how the developed technologies are actually employed and how decision-making authorities consider such technologies in their projects. Given that the ultimate goal of all research activities is to provide end-use sectors with necessary information, answers to these questions are as important as technical investigations. This case study discusses the state of the practice of FRP composites for highway infrastructure. So informed, both transportation agencies and researchers will be aware of barriers that impede the use of FRPs and will identify directions toward future research and planning.

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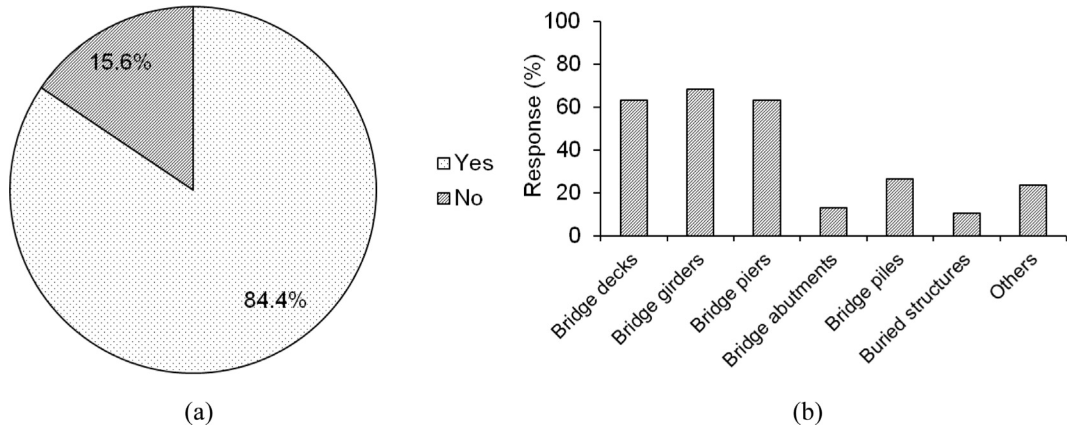

Fig. 1. Has your agency used FRP composites for highway infrastructure (45 answers from 45 responding agencies): (a) previous experience; (b) application of FRP (multiple items selected).

2. Research significance

The recent development of FRP composites and corresponding applications are noteworthy in civil infrastructure. A great deal of research effort has been expended to examine the behavior and performance of FRP-based structural members. However, the actual use of FRP materials is not well documented and a comprehensive assessment is sparse whether they have been actively adopted by state and federal jurisdictions. The reason is that the preponderance of existing studies involves technical aspects that are not balanced with in-situ implementation. The present paper is intended to expand the purview of FRP technologies for the sake of the bridge engineering community by appreciating current limitations and challenges, as well as the gaps between the research and practice. In so doing, the full breadth of FRP applications is elucidated and technology transfer can better be accomplished.

3. State-of-current-practice survey

A survey questionnaire is disseminated to the state DOTs and Canadian Ministry of Transportation (provincial ministries), in corporation with the American Association of State Highway Transportation Officials (AASHTO) Subcommittee on Bridges and Structures (SCOBS). The objective of this survey is to establish the state of current practice of FRP technologies in highway infrastructure, including present implementation, concerns, suggestions, and future directions. Survey results are also considered as a metric to identify the gap between the state-of-the-art research and actual practice.

3.1. Overview

The survey was designed to provide information on the following items:

- How state DOTs are using FRP, with a summary of use by application
- Whether FRP use is experimental or an institutionalized standard practice
- Lessons learned by state DOTs in applications of FRP
- Challenges to implementation
- What specifications have been used by state DOTs
- What design guidelines have been used by state DOTs
- Procurement and contracting methods
- Long-term durability and performance
- Performance evaluation and qualification testing being conducted by state DOTs
- Research being conducted by the state
- Cost considerations in the use of FRP, how cost impacts the decision for FRP use, and how FRP is incorporated into life-cycle cost analysis
- How FRP is being used in repair and retrofit versus new construction projects

A total of 46 transportation agencies responded to the questionnaire (44 US DOTs and 2 Canadian Provincial Ministries of Transportation: an 88% response rate of the US agencies). To facilitate the survey process, an online survey program was employed. Phone interviews were conducted to better understand the responses and suggestions of the agencies (18 respondents, excluding the agencies showing similar responses and those with the panel members). The survey data were summarized in three content groups as follows:

- *Historical aspect of FRP composites in highway infrastructure*: the first part of survey was concerned with the general experience of the responding agencies (e.g., when FRP-applications began, how many projects had been completed, and which bridge members were constructed with FRP composites)
- *Use of FRP composites*: specific information was gathered on how the respondents utilized FRP technologies for their construction projects in terms of specifications, testing and evaluation, maintenance, durability assessment, technical challenges, life cycle costs, research activities, procurement, and overall assessment.
- *Project planning with FRP composites*: future construction trends using FRP were briefed in this content group. A discussion on why some agencies did not use FRP composites was provided, although there are a number of advantages.

3.2. Historical aspect of FRP composites in highway infrastructure

More than 80% of the respondents used FRP composites for their projects (38 agencies), as shown in Fig. 1(a). Bridge girders were the most frequently used members (68.4%), including CFRP-prestressed concrete girders, followed by bridge decks and piers (63.2% and 63.2%, respectively) and piles (26.3%). Other FRP applications (23.7%) include concrete pavement (FRP dowels), a floating bridge, fender piles, bridge drains, shear walls, bent cap wrapping, and culvert invert liners. It is noted that significant portions of the *Others* category were left blank and were redundant with the items listed in Fig. 1(b). Although the agencies did not specifically indicate FRP types used in their projects, according to the interview, GFRP bars were employed as reinforcement for bridge decks and buried structures, and CFRP and GFRP sheets were used to strengthen bridge girders and columns. Fig. 2 exhibits the application history of FRP materials. A pioneering effort was observed during the period between 1990 and 1995 (21.1%), when FRP technologies were transferred from the mechanical and aeronautics

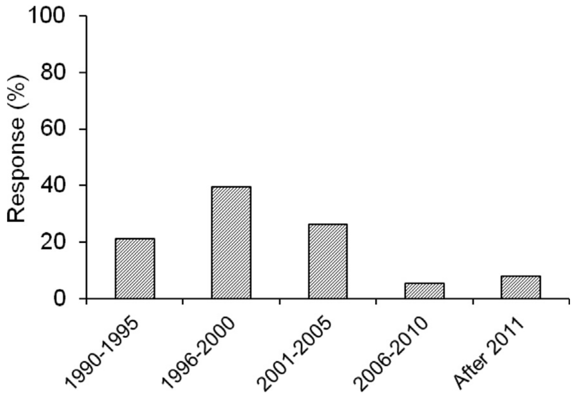

Fig. 2. When was the first time for your agency to use FRP composites (38 answers from 38 agencies experiencing FRP).

industries to the civil structure community. A significant increase was achieved up to 65.8% during the 1996–2000 (39.5%) and 2001–2005 (26.3%) periods. For the last ten years (2006–2016), 13.2% of the responding agencies began to adopt FRP for construction projects.

Depending upon structure types, some transportation agencies consider FRP technologies to be a standard practice, whereas others still regard them as experimental (or developmental). The term *standard practice* is defined as a technique that can be readily implemented by a state DOT with familiar construction materials (FRP composites in the present survey), based on established specifications. According to Table 1, strengthening constructed bridge piers (columns) accounts for 44.7% of the *Standard practice* category. It should be noted that a bridge pier consists of vertical and horizontal load-bearing members (column and pier-cap, respectively), and CFRP-strengthening can be implemented for both members. CFRP-confinement is a convenient and competitive solution compared with steel jacketing. Reasonable amounts of bridge decks and girders account for the *Standard practice* category as well (13.2% and 26.3%, respectively). The distribution of the *Experimental* category was as follows: bridge decks (63.2%), bridge girders (44.7%), bridge piers or columns (28.9%), bridge piles (28.9%), bridge abutments (17.9%), buried structures (17.9%), and others (15.4%). Table 1 enumerates the outline of various FRP applications at the member level, rather than specific implementation details including several sub-branches that are not readily achievable in an online survey program with numerous respondents (e.g., the *Bridge decks* category can be subdivided into new deck construction and strengthening (retrofit and repair) with EB (externally bonded) and NSM (near-surface-mounted) methods based on GFRP or CFRP materials). These observations imply that FRP has been used for many projects; however, it needs more development in terms of implementation techniques and specifications (further discussions follow). The *Others* item included a number of redundant responses that could be answered in the listed *Member* items (e.g., FRP rebar, FRP strengthening, FRP wrap, pier cap, deck overhang with NSM FRP, repair for impact damage, prestressing and post-tensioning strands, and substructure repair), except some answers concerning GFRP dowel bars for concrete pavement and sidewalks over wingwalls. Some respondents noted that the *Experimental* and *Standard practice* categories are determined on an element basis. The follow-up interview revealed that more field projects with FRP composites would be required for state DOTs to consider this technology as a standard practice.

Table 1
Does your agency consider whether FRP use is experimental or a standard practice, based on previous experiences (multiple items selected; 38 answers from 38 agencies experiencing FRP).

Member	Experimental	Standard practice	Not applicable
Bridge decks	63%	13%	24%
Bridge girders	45%	26%	26%
Bridge piers	29%	45%	21%
Bridge abutments	18%	5%	67%
Bridge piles	28%	5%	51%
Buried structures	18%	10%	59%
Others	15%	10%	49%

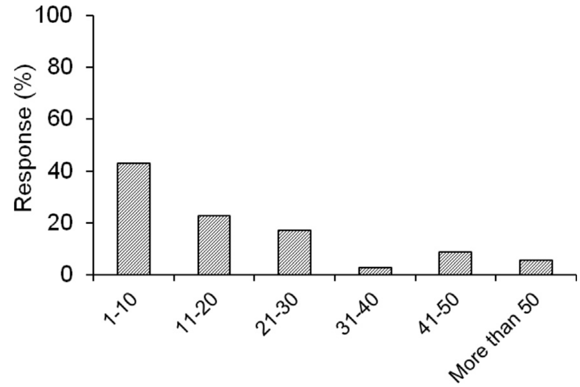

Fig. 3. Estimate how many projects were completed with FRP composites in your agency thus far (38 answers from 38 agencies experiencing FRP).

Over 40% of the jurisdictions had 10 or fewer FRP-based projects, as shown in Fig. 3, indicating that the use of FRP composites is still premature from an application standpoint. Specific reasons for this low adoption rate are explained in subsequent sections. The agencies reasonably employed FRP (22.9% for 11–20 projects and 17.1% for 21–30 projects). It is remarkable to note that 14.3% of the respondents used FRP materials more than 40 and 50 times (8.6% and 5.7%, respectively). This illustrates that, once transportation agencies become accustomed to using FRP materials, they can be a strong alternative to conventional materials with notable benefits. More field-demonstration projects are necessary to actively promote FRP composites, including technology transfer in professional meetings, workshops, and conferences. During the phone interviews, several agencies mentioned that technical training is necessary to better understand FRP materials and their applications in highway infrastructure. Some agencies specifically indicated webinars, while others preferred on-site training that provides direct interaction with the instructors.

3.3. Use of FRP composites

The majority of the transportation agencies referenced design and practice guidelines published by AASHTO and ACI 440, as shown in Fig. 4. The portion of in-house specifications accounted for 21.1% of the response (California, Florida, Georgia, Indiana, Iowa, New York,

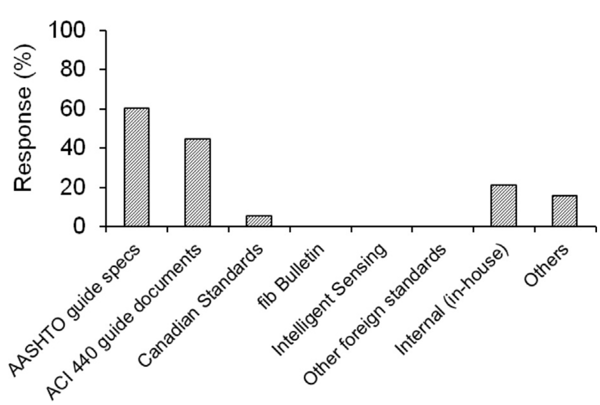

Fig. 4. Which design guides/specifications for FRP have been used in your agency (multiple items selected; 38 answers from 38 agencies experiencing FRP).

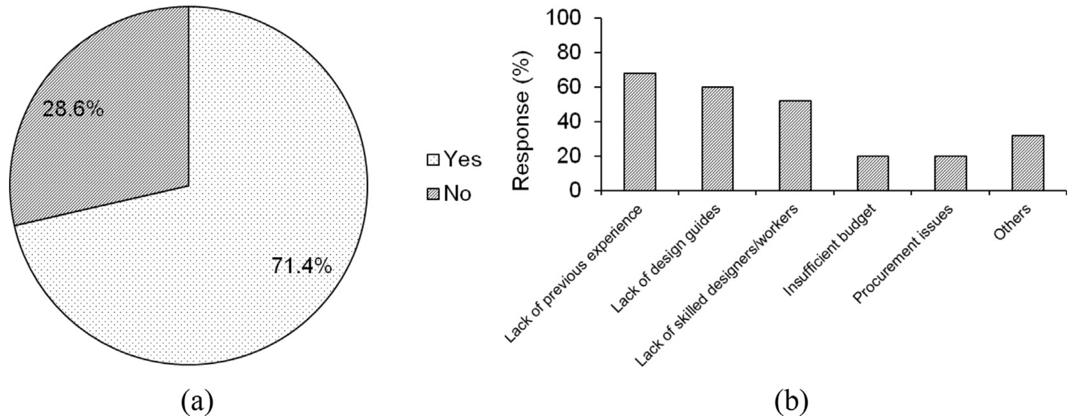

Fig. 5. Has your agency had any challenges in using FRP for infrastructure projects (35 answers from 38 agencies experiencing FRP): (a) response; (b) sources of challenges (multiple items selected).

Vermont, and Virginia). These in-house documents were developed based on the agencies' own experience (according to phone conversations with the agencies), which might fill specific application gaps that were not stated in other national-level documents, such as the AASHTO guide specifications and ACI 440 manuals. Although Canadian standards were used by some agencies (5.3%), the dependency of foreign documents (i.e., *fib* bulletins and Intelligent Sensing for Innovative Structures Network design manuals) was virtually none. The *Others* category (15.8%) included the following comments: FRP manufacturers, ICC Evaluation Service- ESR-2103 for material qualification standards, and consultant design. The need for unified practice standards for FRP arises, as in the case of the AASHTO LRFD Bridge Design Specifications (several agencies mentioned these unified standards during the interviews), which result in the uniform application and management of FRP-based structures, regardless of performing agencies.

Fig. 5 demonstrates technical and administrative challenges experienced by the responding jurisdictions, when employing FRP composites. More than 70% of the agencies answered that they had challenges (Fig. 5(a)). Specifically, insufficient experience (68.0%) and a lack of design guidelines (60.0%) were top ranked, followed by a lack of skilled designers and workers (52.0%), as shown in Fig. 5(b). These responses clarify the reasons (i) why FRP was not actively used in many state agencies and (ii) why the agencies familiar with FRP employed it more than 40 times in their projects. As discussed earlier, the transportation agencies generally acknowledge the benefits of FRP application and, accordingly, active technology transfer will facilitate the adoption of this promising construction material. Nontechnical issues such as insufficient budget (20.0%) and procurement (20.0%) also influenced the use of FRP for infrastructure projects. Given that procurement in state DOTs is sometimes processed with pre-registered vendors, FRP manufacturers might be administratively disadvantageous when competing with others.

About 45% of the respondents conducted qualification tests for FRP materials, as shown in Fig. 6. Mechanical testing was 75.0% and durability testing was 56.3%, which are the most important aspects in FRP applications on site. Other methods utilized were bond examinations using non-destructive evaluation (NDE), pull-off tests, scaled column tests, and shake tables including multi-span bridges. One agency contracted with a university to develop environmental reduction factors. The respondents were interested in the performance of structural members constructed with FRP composites (Fig. 7). The most common method was visual inspection (83.3%), which is relatively easy to conduct with minimal costs. The portion of the performance evaluation using special equipment was remarkable: non-destructive testing (61.1%) and condition rating (44.4%). The 16.7% response in the *Others* category included load testing, along with computer-based modeling (basically redundant with the condition rating item).

The performance of FRP-based structures was satisfactory, as shown in Fig. 8. In most cases, the maintenance and repair of these structures were not required (76.5%). The occurrence of technical action for structural members reinforced with FRP bars was none, and for the members strengthened with FRP sheets was insignificant (only three states indicated that maintenance and repair were necessary for FRP-strengthened members: three times for the last 16 years in one state, one time for the last 10 years in another state, and 8 times for 10 years in the other state primarily due to local debonding in association with workmanship and external sources such as impact and fire). Other FRP types required technical action; for instance, FRP decks delaminated owing to stiffness incompatibility or inappropriately designed connections details, and ultimately had to be replaced with a conventional reinforced concrete deck (one state indicated 8 times for 5 years). Although a comparative analysis with conventional materials (e.g., steel) was outside the scope of the present study, it could be concluded that FRP applications need negligible maintenance and repair action, supported by the survey results and interviews with the participating agencies.

Also of interest was the long-term durability of installed FRP composites, as evidenced by the 69.4% response in Fig. 9(a). Durability is a major concern to most transportation agencies, because the application history of FRP materials is relatively short and their actual time-dependent behavior on site is not well documented. Most agencies conducted visual inspections (88.0%) to examine the durability performance of structures with FRP (Fig. 9(b)). Non-destructive testing (32.0%) was used in preference to destructive testing (24.0%), which is typical since the agencies did not want to damage existing structures. Another method belonging to durability assessment was accelerated laboratory testing.

Life-cycle cost analysis is an important component in FRP application. However, only 8.6% of the responding agencies examined the life-cycle costs associated with FRP-based projects (Fig. 10). These agencies used present-worth and risk analyses, and assessed the costs of CFRP-prestressed concrete girders relative to those of conventional steel-prestressed girders. Effort on life cycle cost analysis appears insufficient to quantify the long-term benefit of FRP applications in highway infrastructure.

The investment of the respondents in research is substantial [Fig. 11(a)]. The responding agencies supported structure level and in-situ level research projects [Fig. 11(b)], and 53.8% were interested in material level research. Some agencies checked the *Others* category (26.9%) with the following comments (most answers in this category were redundant with the foregoing categories): barrier static load testing, and appropriateness of design standards (ACI versus AASHTO and others).

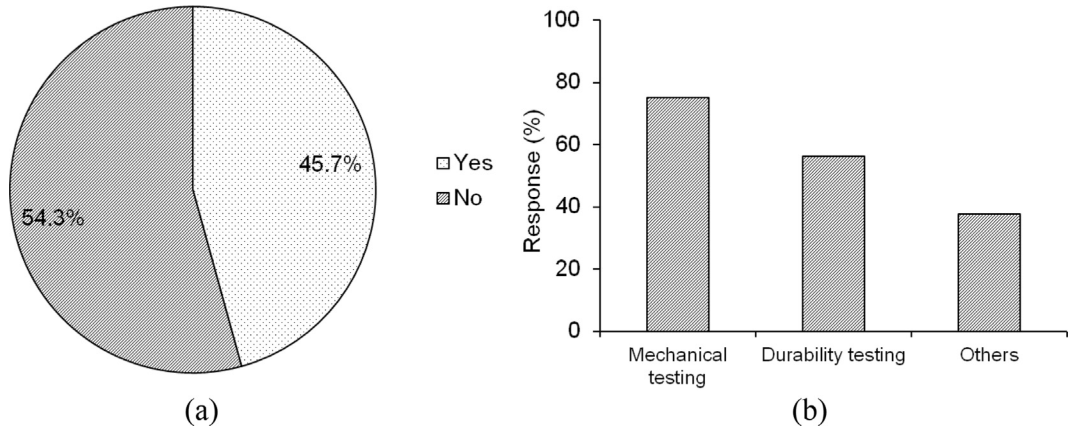

Fig. 6. Has your agency conducted qualification testing (e.g., strength, durability, and the like) for FRP materials or FRP-based structures (35 answers from 38 agencies experiencing FRP): (a) response; (b) details (multiple items selected).

The agencies responding to the previous question (Fig. 11) stated that research activities can facilitate the use of FRP composites in practice (Fig. 12(a)). Three subject areas (Failure characteristics (62.5%), Performance evaluation (62.5%), and Specification development (62.5%)) received closer attention than other areas. As shown in Fig. 13 (some agencies checked both Yes and No options, and this type of answer was not counted), the majority of the responding jurisdictions did not prefer FRP-based rehabilitation to conventional approaches. It is again confirmed that the transportation agencies are not certain about the long-term performance and durability of installed FRP composites. Attention from the research community is required to address this fundamental concern associated with FRP-based construction. More than 28% of the agencies preferred structural rehabilitation with FRP (Fig. 13).

Fig. 14 exhibits the opinion of the transportation agencies on FRP costs. Almost 60% of the responders answered that costs are a barrier to accepting FRP technologies [Fig. 14(a)], and 28.6% indicated that costs are significantly high [Fig. 14(b)]. Fig. 15 shows an overall evaluation of FRP-based projects from the perspective of transportation agencies. The agencies were generally satisfied with the use of FRP composites. Phone interview with 18 agencies revealed the same result: 17 agencies did not have a serious concern about the performance of installed FRP composites within their observation ranges; however, one agency was not sure about cost-benefit from FRP applications.

3.4. Project planning with FRP composites

Fig. 16 shows fundamental reasons why responding jurisdictions were reluctant to consider FRP composites in their projects. Critical issues were a lack of experience (48.5%) and design guides (51.5%), as well as of skilled designers/workers (39.4%). These issues are aligned with the challenges the agencies experienced when pursuing FRP projects (Fig. 5). Given that the experience and design-guide components were consistently ranked higher than other items and are instrumental in FRP application, information-sharing between various entities and jurisdictions appears to be essential for end-users to better utilize this promising construction material. Several agencies mentioned during the phone interviews that contractors need to be knowledgeable about FRP applications. More than 85% of the responding agencies positively

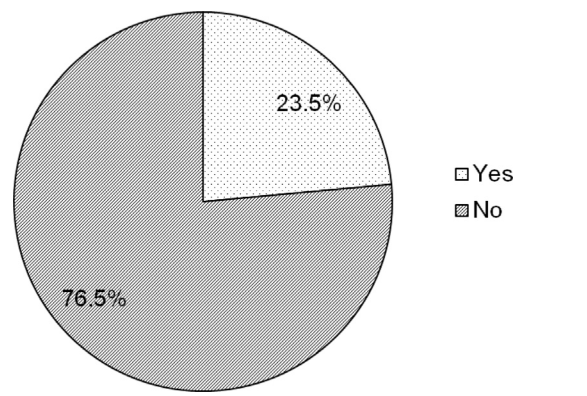

Fig. 8. Has your agency conducted maintenance or repair for structures constructed with FRP (34 answers from 38 agencies experiencing FRP).

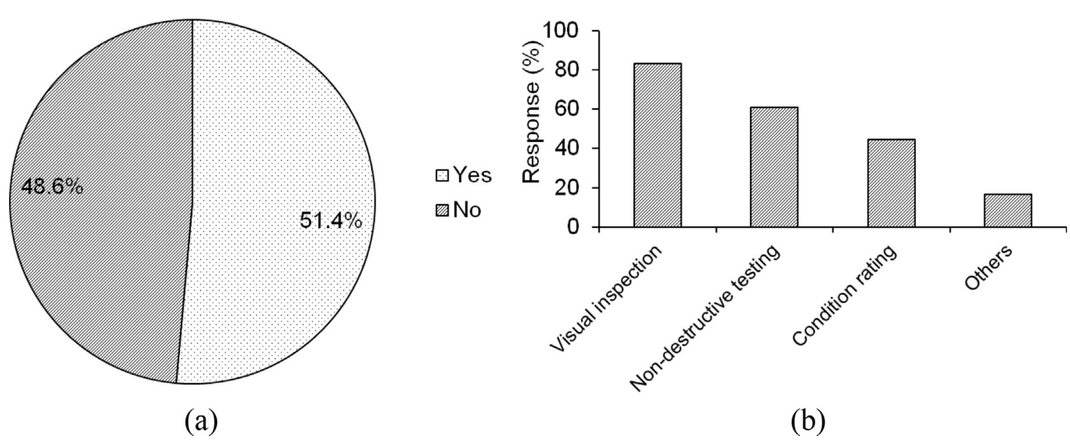

Fig. 7. Has your agency conducted performance evaluation for structures constructed with FRP (35 answers from 38 agencies experiencing FRP): (a) response; (b) details (multiple items selected).

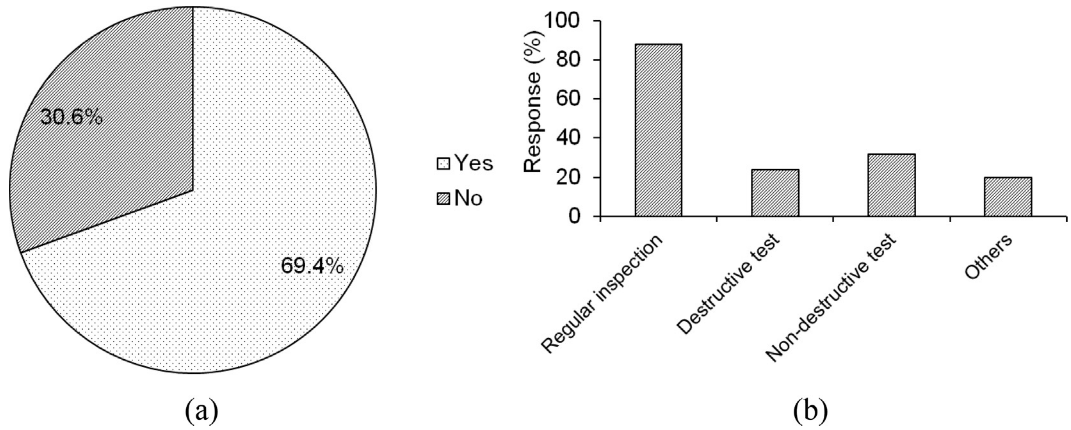

Fig. 9. Has your agency considered or examined the long-term durability of installed FRP (36 answers from 38 agencies experiencing FRP): (a) response; (b) details (multiple items selected).

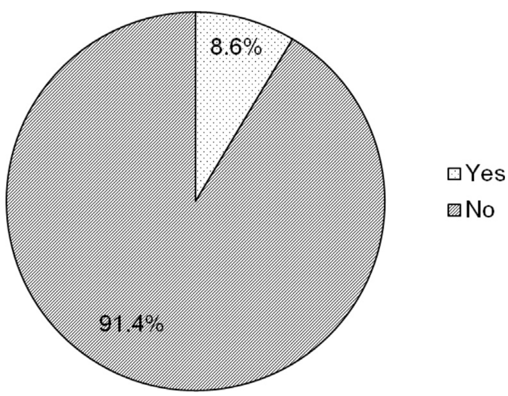

Fig. 10. Has your agency considered or performed life cycle cost analysis using FRP (35 answers from 38 agencies experiencing FRP).

answered the potential of using FRP composites in future projects (29.7% for *Very likely* and 56.8 for *Likely*), as shown in Fig. 17. By contrast, 13.5% of the agencies were not in favor, primarily because of the reasons discussed previously (Fig. 16).

The following is a summary of observations from field work, which may be of interest to state agencies when planning infrastructure construction with FRP materials:

- *FRP-reinforced concrete*: the responding agencies did not indicate specific lessons belonging to FRP-reinforced concrete members.
- *FRP-prestressed concrete*: anchor systems for CFRP tendons need attention, because stress concentrations may damage the tendons during prestressing. When transporting CFRP tendons, at least two workers hold both ends of the tendons as straight as possible to prevent the local bending of the tendons. Improper handling such as excessive bending can degrade the tendon's load-carrying capacity (i.e., fiber kinking).
- *FRP-strengthening*: although premature FRP-debonding has not been reported, protective coatings may deteriorate. Regular inspection detects this non-structural problem, and maintenance action may follow, depending upon the extent of peeled coatings. When unidirectional FRP sheets are bonded for shear strengthening, including U-wrap anchorage, the fiber direction needs to be checked (i.e., perpendicular to the longitudinal span). If fiber direction is parallel to the span, the strengthening effect does not conform to what was intended for the FRP sheets. Prior to bonding FRP sheets or laminates, an inspection for quality control (e.g., surface preparation) precludes potential debonding problems caused by poor workmanship. It is particularly important for wet lay-up application, including the complete saturation of dry fibers. Documentation of all procedures and material details is necessary for future maintenance purposes.
- *FRP decks*: preassembled FRP components increased construction productivity. Improperly designed or detailed deck connections, however, failed prematurely. The leveling and fabrication of FRP deck panels during installation were crucial, because differential deflections between the panels can accelerate connection failure. FRP decks are generally durable, whereas delamination often caused problems and required maintenance. No particular solutions were

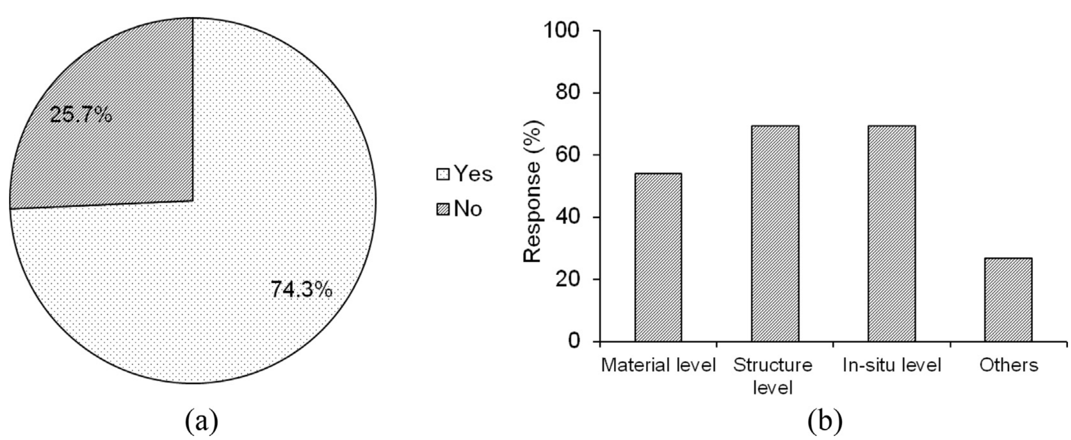

Fig. 11. Has your agency conducted or supported research activities related to FRP application (35 answers from 38 agencies experiencing FRP): (a) response; (b) details (multiple items selected).

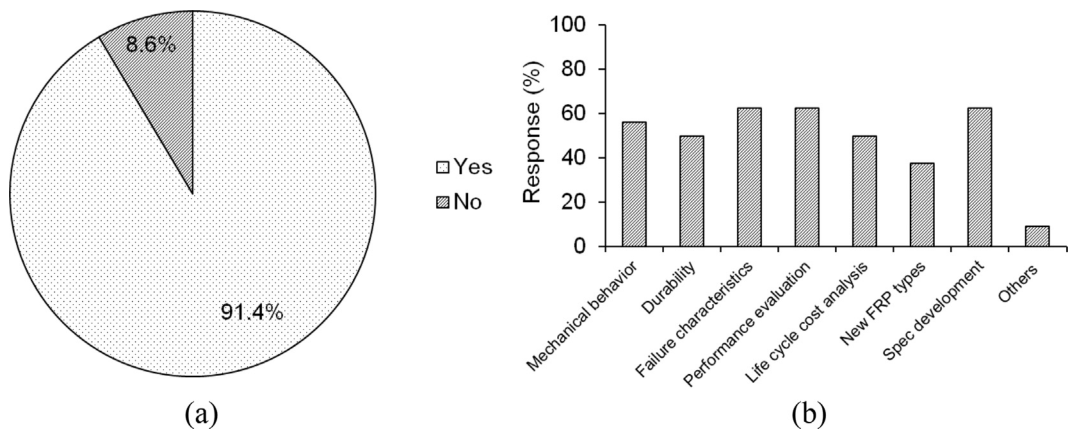

Fig. 12. Do you believe research can facilitate use of FRP composites in practice (35 answers from 38 agencies experiencing FRP): (a) response; (b) details (multiple items selected).

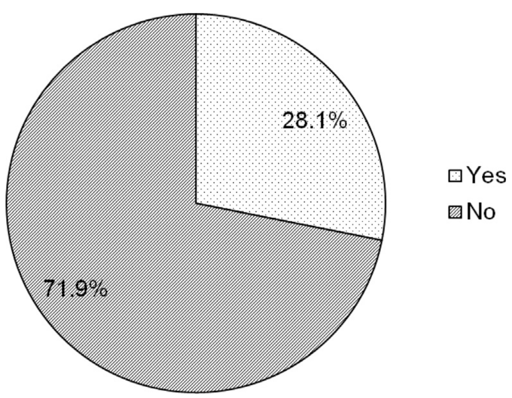

Fig. 13. Does your agency prefer FRP-based rehabilitation (repair/retrofit) for deteriorated structures to conventional techniques (32 answers from 38 agencies experiencing FRP).

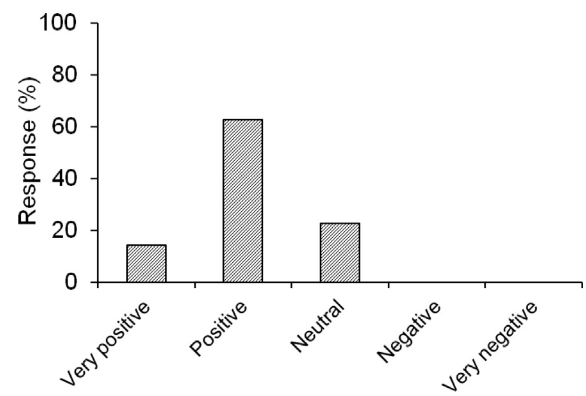

Fig. 15. How do you rate your overall experience in FRP composites for your projects (35 answers from 38 agencies experiencing FRP).

proposed to prevent delamination failure.

4. Summary and conclusions

This case study has presented a comprehensive overview of FRP applications for highway infrastructure. An extensive survey has been conducted to understand the state of current practice of FRP composites in the United States. According to the responses and comments of the participating jurisdictions (44 US DOTs and 2 Canadian agencies), various technical and administrative aspects were examined. The findings of the survey questionnaire and follow-up interviews are as follows:

- Over 80% of the responding agencies used FRP materials for their projects. Specifically, bridge girders, decks and piers (columns), piles, abutment, buried structures, concrete pavement, drains, and culvert liners. The application began in the early 1990s (21.1% of the respondents), whereas most agencies adopted FRP technologies during the period between 1996 and 2005 (65.8% of the respondents).
- FRP applications were considered as a standard practice or experimental, depending upon structural members. CFRP-wrapping for upgrading bridge piers (columns) was the most accepted standard

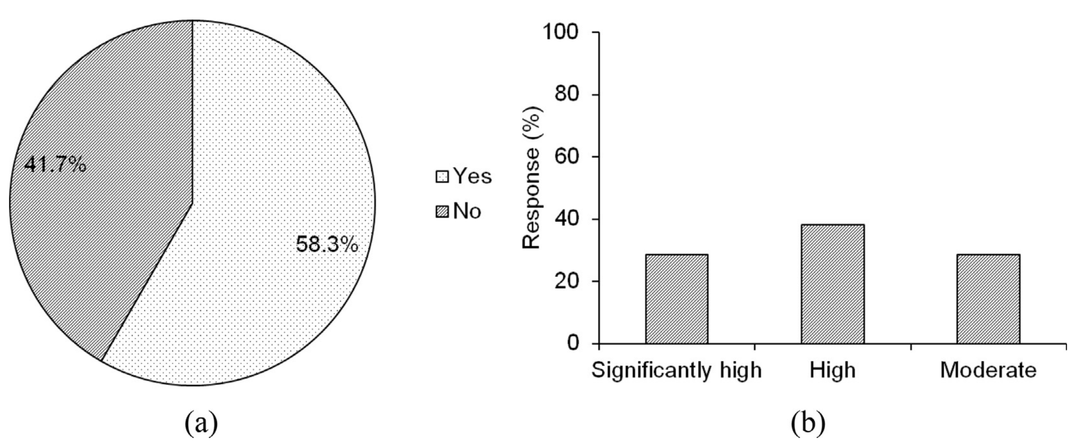

Fig. 14. Do you think costs are a barrier in accepting FRP technologies (36 answers from 38 agencies experiencing FRP): (a) response; (b) details.

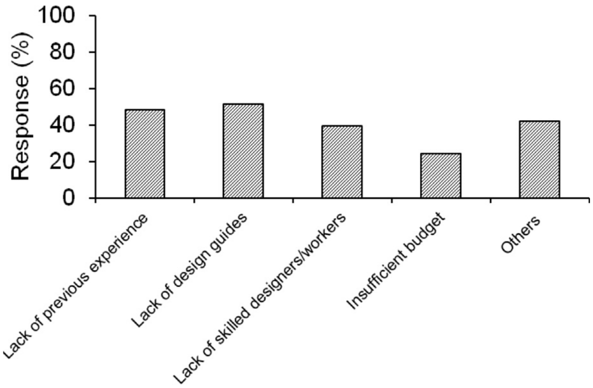

Fig. 16. Why has your agency not considered using FRP for infrastructure projects (multiple items can be selected; 33 answers from 46 responding agencies).

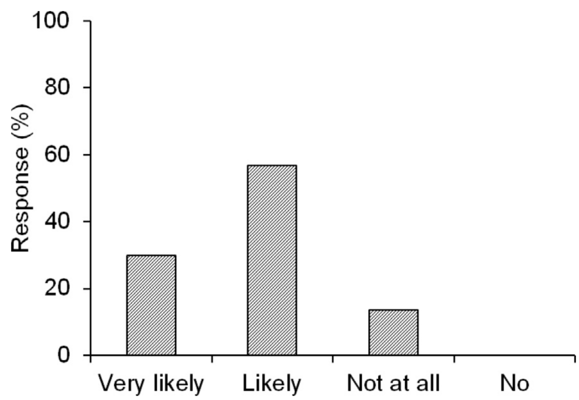

Fig. 17. Is your agency planning to consider use of FRP composites for a future project (37 answers from 46 responding agencies).

practice (44.7% of the respondents), followed by bridge decks and girders with GFRP reinforcing bars and CFRP-strengthening, respectively. A number of agencies, however, still considered FRP applications to be experimental. Almost 45% of the respondents conducted fewer than 10 projects using FRP composites, whereas 14.3% of the respondents had more than 40 projects with FRP.

- When implementing FRP technologies, the agencies referenced guidelines published by AASHTO and ACI 440. In-house specifications were also used. By contrast, foreign recourses such as *fib* bulletins (European guides) were not used at all. Unified practice manuals or specifications concerning FRP composites help produce uniform application quality and management procedures in highway infrastructure.
- Most responding agencies (71.4% of the respondents) had the following challenges in FRP-based projects: insufficient experience, a lack of design guidelines and skilled personnel, procurement, and budget. The agencies conducted qualification tests to evaluate FRP's mechanical and durability performance, including the bond behavior of FRP. Although limited effort was made on supporting research activities, the responding agencies revealed that research can facilitate the use of FRP in practice.
- The performance and long-term durability of constructed structures with FRP were of interest to the transportation agencies. As such, several evaluation methods were employed (e.g., visual inspection, non-destructive testing, and load rating with computer modeling). It was found that the performance of structures was satisfactory with negligible demand for maintenance and repair. Nonetheless, long-term durability requires further examinations. Life-cycle cost analysis also needs more attention to better quantify the economic benefit of FRP application.
- On procurement and contractor selection for FRP-based projects, procedures were basically the same as those of conventional projects. Some agencies, however, noted that sole sourcing is necessary for FRP with a special provision or separate contract.
- The respondents were mostly satisfied with FRP in their projects, even though there were some minor problems (e.g., deteriorated surface coating). Several agencies have current and planned projects using FRP composites; for instance, CFRP-prestressed girders, CFRP-wrapping for columns, hybrid and GFRP decks, and composite piles.

Despite the extensive endeavors discussed above, further research and development are necessary to advance the state-of-the-art and state-of-the-practice of FRP composites in highway infrastructure:

- *FRP-reinforced concrete*:
  - o globally acceptable expressions for deformability
  - o long-term in-situ monitoring for durability assessment
  - o further testing of FRP-reinforced columns and developing design guidelines
  - o material characterization of BFRP and application, including fatigue investigations
- *FRP-prestressed concrete*:
  - o time-dependent prestress losses
  - o prediction of long-term camber and deflection
  - o in-situ behavior of installed FRP tendons and anchorage
- *FRP-strengthened concrete*:
  - o specification development for strengthening steel and timber structures
  - o size effect on the behavior of strengthened members
  - o environmental reduction factors for various exposure conditions
  - o anchoring techniques to preclude debonding
- *Others*:
  - o integrated FRP decks to prevent premature delamination failure
  - o specification development for FRP stay-in-place members and FRP decks
  - o examination of life cycle costs for constructed FRP-based structures

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