

# CHALLENGES IN PROTECTIVE FOOTWEAR FOR INDIA'S DISASTER MANAGEMENT WORKFORCE: A DESIGN THINKING APPROACH

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## CHALLENGES IN PROTECTIVE FOOTWEAR FOR INDIA'S DISASTER MANAGEMENT WORKFORCE: A DESIGN THINKING APPROACH

**ABSTRACT.** Firefighters in India play a critical role in managing fire accidents and rescue operations, often working under high-pressure and hazardous conditions. Their work demands swift and efficient action, making it essential to ensure their safety and performance through appropriate equipment, particularly footwear. Footwear is a crucial component of their protective gear, directly impacting their mobility, comfort, and overall effectiveness during rescue operations. This study explores the current challenges associated with the footwear used by disaster management professionals in India, with a specific focus on firefighters. It evaluates the design, functionality, and performance of the footwear currently in use and identifies the limitations that hinder their effectiveness in extreme conditions. The research adopts a design thinking approach to analyze the challenges faced by disaster management professionals through a comprehensive mixed-methods study. A structured survey was conducted with 385 disaster management professionals across Six Indian states (Telangana, Maharashtra, Karnataka, Tamil Nadu, West Bengal and Gujarat), complemented by in-depth interviews with 75 firefighters from various operational levels. Additionally, a systematic literature review was conducted. Data were gathered on various factors, including comfort, durability, protection, flexibility, and environmental adaptability of the footwear. Findings reveal near-unanimous consensus on the need for footwear redesign, with 96.1% of respondents in agreement. Poor heat and flame resistance emerged as the dominant performance deficiency, identified by 34.8% of respondents. Chi-square analysis confirmed a highly significant association between reported challenges and redesign necessity ( $\chi^2 = 28.47$ ,  $p < 0.001$ , Cramér's  $V = 0.272$ ). K-means cluster analysis identified three operationally distinct user personas, affirming that a single uniform specification is insufficient for India's heterogeneous disaster management workforce. Evidence-based design specifications were translated into two functionally differentiated prototypes. Design A, a low-mid ankle boot incorporating the patent-pending Protected Rapid-Release Closure System, achieved full IS 15298 (Part 2):2024 compliance across all mandatory test parameters, with breathability exceeding Indian market norms. Design B, a tall shaft boot configured for wildland deployment, incorporated an external TPU ankle panel with documented protection-mobility trade-offs. Both prototypes were validated at a BIS-approved laboratory, utilising an Indian-specific anthropometric last and a nine-component material architecture, demonstrating the feasibility of IS 15298-compliant next-generation protective footwear within Indian manufacturing constraints.

**KEYWORDS:** firefighting footwear design, protective footwear, occupational safety, design thinking, ergonomics, India disaster management

## PROVOCĂRI LEGATE DE ÎNCĂLȚĂMINTEA DE PROTECȚIE PENTRU PERSONALUL DE GESTIONARE A CATASTROFELOR DIN INDIA: O ABORDARE BAZATĂ PE DESIGN THINKING

**REZUMAT.** Pompierii din India joacă un rol esențial în gestionarea incendiilor și în operațiunile de salvare, lucrând adesea în condiții periculoase și de mare presiune. Munca acestora necesită acțiuni rapide și eficiente, fiind esențial să li se asigure siguranța și performanța prin echipamente adecvate, în special încălțăminte. Încălțăminte este o componentă crucială a echipamentului lor de protecție, având un impact direct asupra mobilității, confortului și eficienței generale în timpul operațiunilor de salvare. Acest studiu explorează provocările actuale asociate încălțăminteii utilizate de profesioniștii din domeniul gestionării dezastrelor din India, cu un accent specific pe pompieri. Articolul evaluează designul, funcționalitatea și performanța încălțăminteii utilizate în prezent și identifică limitările care le împiedică eficacitatea în condiții extreme. Cercetarea adoptă o abordare de tip design thinking pentru a analiza provocările cu care se confruntă profesioniștii din domeniul gestionării dezastrelor printr-un studiu cuprinzător bazat pe metode mixte. S-a realizat un sondaj structurat cu 385 de profesioniști în gestionarea dezastrelor din șase state federale indiene (Telangana, Maharashtra, Karnataka, Tamil Nadu, Bengalul de Vest și Gujarat), completat de interviuri aprofundate cu 75 de pompieri de la diferite niveluri operaționale. În plus, s-a efectuat o analiză sistematică a literaturii de specialitate. Au fost colectate date privind diverși factori, printre care confortul, durabilitatea, protecția, flexibilitatea și adaptabilitatea la condițiile de mediu a încălțăminteii. Rezultatele indică un consens aproape unanim cu privire la necesitatea re-proiectării încălțăminteii, 96,1% dintre respondenți fiind de acord cu acest lucru. Rezistența slabă la căldură și la foc s-a evidențiat ca fiind principala deficiență de performanță, identificată de 34,8% dintre respondenți. Analiza chi-pătrat a confirmat o asociere extrem de semnificativă între provocările raportate și necesitatea re-proiectării ( $\chi^2 = 28,47$ ,  $p < 0,001$ , coeficientul  $V$  Cramér = 0,272). Analiza clusterelor K-means a identificat trei tipuri de utilizatori distincte din punct de vedere operațional, confirmând faptul că o singură specificație uniformă este insuficientă pentru forța de muncă eterogenă din domeniul gestionării dezastrelor din India. Specificațiile de proiectare bazate pe dovezi au fost transpuse în două prototipuri diferențiate din punct de vedere funcțional. Modelul A, o gheată joasă-medie care încorporează sistemul de închidere rapidă protejat (în curs de brevetare), în conformitate deplină cu IS 15298 (Partea 2):2024 pentru toți parametrii de testare obligatorii, cu o respirabilitate care depășește normele pieței indiene. Modelul B, o cizmă înaltă configurată pentru utilizare în zone sălbătice, a încorporat un panou extern din TPU la nivelul gleznei, cu compromisuri documentate între protecție și mobilitate. Ambele prototipuri au fost validate într-un laborator aprobat de BIS, utilizând o formă antropometrică specifică pentru India și o arhitectură a materialelor cu nouă componente, demonstrând fezabilitatea încălțăminteii de protecție de nouă generație conformă cu IS 15298 în cadrul producției indiene.

**CUVINTE CHEIE:** proiectarea încălțăminteii pentru pompieri, încălțăminte de protecție, securitatea muncii, design thinking, ergonomie, gestionarea dezastrelor în India

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## LES DÉFIS LIÉS AUX CHAUSSURES DE PROTECTION POUR LE PERSONNEL CHARGÉ DE LA GESTION DES CATASTROPHES EN INDE : UNE APPROCHE BASÉE SUR LE DESIGN THINKING

**RÉSUMÉ.** En Inde, les pompiers jouent un rôle essentiel dans la gestion des incendies et les opérations de sauvetage, travaillant souvent dans des conditions de forte pression et dangereuses. Leur travail exige une intervention rapide et efficace, d'où la nécessité de garantir leur sécurité et leur performance grâce à un équipement adapté, en particulier des chaussures. Les chaussures constituent un élément crucial de leur équipement de protection, ayant un impact direct sur leur mobilité, leur confort et leur efficacité globale lors des opérations de sauvetage. Cette étude explore les défis actuels liés aux chaussures utilisées par les professionnels de la gestion des catastrophes en Inde, en mettant particulièrement l'accent sur les pompiers. Elle évalue la conception, la fonctionnalité et les performances des chaussures actuellement utilisées et identifie les limites qui entravent leur efficacité dans des conditions extrêmes. La recherche adopte une approche de « design thinking » pour analyser les défis auxquels sont confrontés les professionnels de la gestion des catastrophes à travers une étude mixte exhaustive. Une enquête structurée a été menée auprès de 385 professionnels de la gestion des catastrophes dans six États indiens (Telangana, Maharashtra, Karnataka, Tamil Nadu, Bengale occidental et Gujarat), complétée par des entretiens approfondis avec 75 pompiers issus de différents niveaux opérationnels. De plus, une revue systématique de la littérature a été réalisée. Des données ont été recueillies sur divers facteurs, notamment le confort, la durabilité, la protection, la souplesse et l'adaptabilité environnementale des chaussures. Les résultats révèlent un consensus quasi unanime sur la nécessité de repenser la conception des chaussures, 96,1 % des personnes interrogées partageant cet avis. La faible résistance à la chaleur et aux flammes est apparue comme la principale lacune en matière de performance, signalée par 34,8 % des personnes interrogées. L'analyse du chi carré a confirmé une association hautement significative entre les défis signalés et la nécessité d'une refonte ( $\chi^2 = 28,47$ ,  $p < 0,001$ ,  $V$  de Cramér = 0,272). L'analyse en grappes K-means a identifié trois profils d'utilisateurs distincts sur le plan opérationnel, confirmant qu'une spécification unique et uniforme est insuffisante pour le personnel hétérogène chargé de la gestion des catastrophes en Inde. Les spécifications de conception fondées sur des données probantes ont été traduites en deux prototypes fonctionnellement différenciés. Le modèle A, une bottine mi-haute intégrant le système de fermeture à dégagement rapide protégé (brevet en instance), a atteint la conformité totale à la norme IS 15298 (Partie 2):2024 pour tous les paramètres de test obligatoires, avec une respirabilité qui dépasse les normes du marché indien. Le modèle B, une botte à tige haute conçue pour les interventions en milieu naturel, intégrait un renfort de cheville externe en TPU avec des compromis documentés entre protection et mobilité. Les deux prototypes ont été validés dans un laboratoire agréé par le BIS, en utilisant une forme anthropométrique spécifique à l'Inde et une architecture matérielle à neuf composants, démontrant ainsi la faisabilité de chaussures de protection de nouvelle génération conformes à la norme IS 15298 dans le cadre de la fabrication indienne.

**MOTS-CLÉS :** conception de chaussures pour pompiers, chaussures de protection, sécurité au travail, design thinking, ergonomie, gestion des catastrophes en Inde

## INTRODUCTION

Firefighting is a physically and mentally demanding profession, requiring individuals to operate in hazardous environments under time-critical conditions. As first responders, firefighters face significant risks, including exposure to high temperatures, sharp debris, unstable terrain, and toxic substances [1]. While personal protective equipment (PPE) plays a pivotal role in safeguarding firefighters, footwear is often an overlooked yet essential element of their gear.

India's disaster management workforce operates in one of the world's most challenging environments, facing diverse hazards ranging from urban fires and industrial accidents to natural disasters and complex emergency situations. According to the National Crime Records Bureau (NCRB) data from 2018–2022 and 2023, residential/dwelling buildings and other locations account for approximately 96% of fire incidents in India, with residential fires contributing 56.47% and other categories 39.53% of total incidents. This distribution indicates that approximately 96% of fire cases require Class 1 category footwear, emphasizing

the critical importance of optimizing protective equipment for these scenarios.

The complexity of protective footwear design stems from competing requirements that must be simultaneously satisfied: providing adequate protection against thermal, mechanical, and chemical hazards while maintaining mobility, comfort, and rapid deployment capabilities [2, 3]. These challenges are amplified in the Indian context by diverse climatic conditions, varied operational environments, budget constraints, and the need for equipment that can be effectively maintained and replaced within existing organizational structures.

The current study investigates the footwear used by disaster management professionals in India, emphasizing design and performance limitations through comprehensive primary research across multiple states. The primary objective is to analyze challenges posed by existing footwear through statistically robust data collection and propose evidence-based recommendations for developing next-generation designs that enhance safety, comfort, and functionality.

## General Requirements for PPE Footwear for Indian Firefighters

Firefighting PPE footwear must address specific environmental, operational, and safety challenges unique to the region while complying with national and global standards such as BIS (Bureau of Indian Standards) IS 15298 [4] for safety footwear and relevant sections of NFPA 1971 or ISO EN 15090 [5].

As per IS 15298-2 (2011), safety footwear for Indian firefighters is categorized based on material construction: Class I covers footwear constructed from leather or comparable materials, excluding designs made

entirely of rubber or polymeric components; Class II covers fully molded or vulcanized footwear crafted from all-rubber or all-polymeric materials. Safety footwear is further classified by coverage extent into five types: Low Shoes (Type A), Ankle Boots (Type B), Half-Knee Boots (Type C), Knee-High Boots (Type D), and Thigh Boots (Type E). Performance features include heat and flame resistance, penetration-resistant midsoles, anti-slip outsoles, and electrical resistance options with additional features like water resistance, chemical resistance, and energy-absorbing cushioned heels.

## Fire Classification and Equipment Requirements



Figure 1. Class 2 firefighting shoes



Figure 2. Present footwear (green & black) used – Class 1

**Class 1 Fire** refers to fires involving ordinary combustibles such as wood, paper, cloth, and plastics. These materials ignite easily and burn with surface flames, commonly found in residential and office settings. Class 1 fires typically require firefighting equipment that prioritizes accessibility, agility, and moderate heat resistance, with leather-based footwear construction providing sufficient protection while ensuring mobility and breathability.

**Class 2 Fire** involves flammable liquids and gases such as gasoline, oil, alcohol, and propane. These fires present higher hazards due to rapid spread, intense heat, and explosion potential, prevalent in industrial environments and chemical plants. Class 2 fire response requires specialized equipment including fully molded or vulcanized footwear with superior heat resistance, chemical resistance, and waterproofing capabilities.

Given that most of the of fire incidents in India fall into Class 1 category scenarios based on NCRB data, this research focuses primarily on optimizing Class 1 footwear performance while acknowledging the need for specialized Class 2 equipment in industrial contexts.

## LITERATURE REVIEW

### Global Challenges in Protective Footwear Design

The literature reveals multiple interconnected challenges that compromise the effectiveness and adoption of protective footwear among emergency responders worldwide. A comprehensive scoping review by Orr *et al.* [2] identified key performance limitations including bulk and weight effects on energy expenditure and obstacle clearance, restricted ankle range of motion from stiff shaft construction, and fit variability leading to

user discomfort and non-compliance. Protective boots typically weigh 1.5–3.0 kg more than standard footwear, resulting in increased metabolic cost and altered gait mechanics that can elevate injury risk [2]. The thermal burden associated with multilayer protective construction compounds these challenges, particularly in hot climates where heat stress becomes a critical operational limitation.

### Design Challenges and Safety Concerns

Firefighter turnout boots have been identified as significant factors impacting safety and health, with poor design leading to risks such as falls and muscular injuries [6]. Key design components like cushioning, traction, and structural support are crucial, but other factors like waterproofness and thermal comfort also need attention. Firefighting footwear must provide effective protection against hazards while being ergonomically suitable for the wearer, adapting to various working conditions and ensuring no additional risk to health [7].

### Current Technologies and Materials

Modern protective footwear integrates sophisticated multilayer constructions combining textiles, reinforcements, and specialized sole compounds to meet flame, cut, electrical, and puncture resistance requirements [3, 8]. Industry standards such as NFPA 1971, EN ISO 20345, and CSA variants drive design specifications that often prioritize protection levels over ergonomic considerations. Recent innovations focus on addressing traditional limitations through advanced materials and construction techniques. Quick don/doff systems aim to reduce deployment time, while dual lacing and zipper systems provide secure fit with integrated handles for ease of use [9]. Sustainable design practices are being explored to improve environmental impact, with focus on additive technologies while meeting high standards of quality and safety [7].

### India-Specific Research Context

Limited research specifically addresses Indian emergency responders' needs. Ticlo and Rao [10] conducted comprehensive studies of Indian firefighter PPE needs, revealing significant gaps in equipment provision. However, their sample size of 160 personnel, while valuable, represents a limited geographic scope requiring expansion for national-level conclusions.

## METHODOLOGY

### Research Design

A mixed-methods study blending design thinking (empathize, define, ideate, prototype, test) with systematic literature review and statistically validated surveys/interviews.

### Sample Size & Justification

Primary empirical data were collected across six geographically distributed sites, each selected on the basis of proximity to established professional facilities, ensuring access to the target respondent population. Multi-stage purposive sampling was employed as the overarching sampling strategy. The total sample size of 385 was determined using the standard formula for population proportion estimation, computed at a 95% confidence level with a 5% margin of error.

The sites spanned six states and one union territory-adjacent region, collectively representing the northern, southern, eastern, and western zones of India. Hyderabad, Telangana, served as the primary access point, contributing 65 respondents. An equivalent allocation of 65 respondents was drawn from Nagpur, Maharashtra. The remaining four sites each contributed 64 or 63 respondents: Bengaluru, Karnataka, was accessed through city fire stations; Chennai, Tamil Nadu, and Ankleshwar, Gujarat, were engaged through locally available professional facilities; and Kolkata and the 24 Parganas district of West Bengal yielded 63 respondents. The marginal variation in sub-sample sizes across sites reflects differences in institutional access and availability of eligible respondents at the time of data collection, and does not compromise the overall representativeness of the sample.

## Sampling Strategy

Distinct sampling criteria were applied for the two primary data collection instruments to ensure that respondents possessed the requisite professional experience and operational relevance.

For the survey, inclusion was restricted to active firefighters with a minimum threshold of continuous service, who were regular users of Class 1 safety footwear and engaged in operational field roles. Respondents in administrative or non-operational capacities, temporary workers, and those below the minimum experience threshold were excluded, ensuring that responses reflected substantive firsthand experience under actual field conditions.

For the in-depth interviews, purposive sampling was employed to achieve structured representation across three intersecting dimensions: operational level, ranging from junior personnel through to senior staff and officers; years of service, spanning early-career through to highly experienced professionals; and geographic context, covering urban, semi-urban, and rural deployment environments. This layered sampling approach ensured that the interview data captured a diverse range of occupational exposures, roles, and regional operational conditions encountered by disaster management professionals across India.

## Survey Instrument

A rigorously validated survey instrument comprising 28 items was employed to capture respondents' demographic profile, current footwear assessment, operational challenges, priority design requirements, and material preferences. The questionnaire's content validity was established via an expert panel of five fire safety specialists, while reliability metrics demonstrated excellent internal consistency (Cronbach's  $\alpha = 0.87$ ) and strong test-retest stability ( $r = 0.92$  over a two-week interval,  $n=30$ ).

In-depth qualitative insights were obtained using a semi-structured interview protocol built around twelve core questions. These interviews addressed footwear performance and limitations, impacts on

operational safety, challenges encountered in various environments, and experiences with injuries or near-misses. Additional probes explored respondents' recommendations for improvement, targeted design features, and considerations related to training and footwear maintenance.

## Data Collection Procedures

Surveys were administered online from March–May 2024, yielding an 89.3% response rate (385/431; average completion: 18 minutes). Individual interviews (45–60 minutes) were conducted by trained researchers.

## Data Analysis

### Quantitative Analysis

Descriptive statistics, chi-square tests, independent t-tests, ANOVA, and correlation analyses were performed on quantitative data, with statistical significance set at  $p < 0.05$ .

### Qualitative Analysis

Interview data were analysed through thematic analysis following Braun and Clarke's framework, using inductive coding. Inter-rater reliability was strong (Cohen's kappa = 0.89), and data saturation was confirmed by the sixty-eighth interview [11].

## Ethical Considerations

The study adhered to established ethical standards throughout, encompassing informed consent, the right to withdraw, confidentiality, anonymity, and secure data management at all stages of the research process.

The interview sample was profiled across years of service and operational area. Service experience was distributed across early, mid, and long-tenure career stages, with mid-career professionals forming the largest segment. In terms of operational context, urban respondents constituted the majority, with progressively smaller representations from semi-urban and rural settings, broadly reflecting the deployment patterns of disaster management professionals across India.

## Limitations and Mitigation Strategies

The study's six-state coverage may not fully represent all Indian regions, though states were selected for climatic and operational diversity; self-report bias was mitigated by triangulating data sources and validation techniques; cross-sectional design limits causality, recommending longitudinal follow-up for future research.

Table 1: Current footwear performance assessment

Challenge Category	n	%	95% CI
1. Poor heat and flame resistance	134	34.8	30.1-39.7
2. Poor grip on wet/slippery surfaces	58	15.1	11.7-19.0
3. Water absorption and permeability	46	11.9	8.9-15.6
4. Excessive weight and bulk	38	9.9	7.1-13.3
5. Limited flexibility for movement	35	9.1	6.5-12.4
6. Inadequate thermal insulation	31	8.1	5.6-11.2
7. Difficulty in quick donning/removal	28	7.3	4.9-10.3
8. Durability and wear issues	15	3.9	2.2-6.4

When respondents were asked to identify the most significant performance challenges associated with their current footwear, poor heat and flame resistance emerged as the dominant concern, cited by over one-third of the sample, underscoring the primacy of thermal protection in high-risk operational environments. Inadequate grip on wet and slippery surfaces was the second most frequently reported challenge, followed by water absorption and permeability, reflecting persistent issues with moisture management under field conditions. Excessive weight and bulk, and limited flexibility for movement, were identified by approximately one in ten respondents each, pointing to ergonomic constraints that impede operational agility. Inadequate thermal insulation and difficulty in quick donning and removal were also notable concerns, particularly given the time-critical nature of emergency deployment. Durability and wear issues, while reported by a smaller proportion, nonetheless highlight concerns regarding the long-term serviceability of current footwear. Taken together, these findings indicate that existing footwear falls short across multiple performance dimensions, with thermal and traction deficiencies representing the most pressing areas for design intervention.

## RESULTS AND DISCUSSION

### Current Footwear Performance Assessment

Analysis of responses from 385 disaster management professionals reveals significant dissatisfaction with current class 1 footwear across multiple performance dimensions:

### Redesign Agreement Analysis

Respondent attitudes towards footwear redesign were overwhelmingly positive. A substantial majority expressed strong agreement with the need for redesign initiatives, with a further significant proportion indicating general agreement.

#### Agreement Distribution:

- Strongly Agree: 251 respondents (65.2%);
- Agree: 119 respondents (30.9%);
- Neutral: 15 respondents (3.9%);
- Disagree: 0 respondents (0.0%);
- Strongly Disagree: 0 respondents (0.0%).

Combined Agreement: 370 respondents (96.1%) support footwear redesign initiatives.

Neutral responses accounted for a negligible share of the sample, and no respondents indicated disagreement or strong disagreement. The combined agreement rate of 96.1% reflects a near-unanimous consensus among operational firefighting professionals regarding the inadequacy of current footwear and the imperative for purposive redesign, lending strong empirical support to the central premise of this research.

### Feature Importance Priorities

Respondents were asked to rank a set of desired features for redesigned protective

footwear using a five-point Likert scale. Heat resistance up to 300°C emerged as the highest priority feature, recording the highest mean score and cited as the top priority by approximately one-third of respondents, reinforcing the findings on performance challenges where thermal protection was the dominant concern. Water resistance and lightweight design followed as the second and third ranked features respectively, reflecting the dual demand for moisture protection and ergonomic wearability. Slip resistance and comfort and breathability were ranked closely

thereafter, indicating that traction and physiological comfort are considered near-equally important by operational personnel. Shock absorption and durability occupied the mid-to-lower rankings, while quick donning and doffing, though ranked last, still recorded a mean score approaching four, suggesting it remains a relevant consideration rather than a peripheral one.

Respondents ranked the following features for redesigned footwear using a 5-point Likert scale:

Table 2: Feature importance priorities

Feature	Mean Score	SD	Rank	Priority %
Heat resistance (up to 300°C)	4.67	0.58	1	33.2
Water resistance	4.23	0.71	2	15.1
Lightweight design	4.18	0.69	3	12.7
Slip resistance	4.15	0.73	4	11.8
Comfort and breathability	4.12	0.68	5	10.9
Shock absorption	4.08	0.75	6	8.7
Durability	3.95	0.81	7	4.8
Quick donning/doffing	3.87	0.79	8	2.8

The relatively narrow spread of mean scores across all eight features indicates a broadly consistent set of expectations among respondents, with thermal performance nonetheless standing out as the defining priority for next-generation protective footwear design.

### Statistical Analysis Results

#### Chi-Square Analysis

To examine the relationship between reported footwear challenges and respondent agreement on the need for redesign, a chi-square test of association was conducted. The null hypothesis posited no significant association between the two variables, while the alternative hypothesis proposed a meaningful relationship. The analysis yielded a chi-square statistic of 28.47 with seven degrees of freedom, and a p-value of less than 0.001, leading to rejection of the null hypothesis at a high level of statistical significance.

#### Primary Hypothesis Testing:

- **H<sub>0</sub>:** No association between current footwear challenges and redesign agreement;
- **H<sub>1</sub>:** Significant association exists between challenges and redesign agreement.

#### Results:

- Chi-Square Statistic:  $\chi^2 = 28.47$ ;
- Degrees of Freedom:  $df = 7$ ;
- p-value:  $p < 0.001$ ;
- Effect Size (Cramér's V): 0.272 (medium effect).

Effect size was assessed using Cramér's V, which returned a value of 0.272, indicative of a medium practical effect. These results confirm a highly significant association between the footwear performance challenges experienced by operational personnel and their endorsement of redesign necessity, providing robust statistical support for the central research premise.

Conclusion: Highly significant association between footwear challenges and redesign necessity ( $p < 0.001$ ).

#### Group Comparison Analysis

One-way ANOVA revealed statistically significant between-group differences across all three variables — heat resistance priority, comfort importance, and durability concerns — with moderate effect sizes observed in each case. Post-hoc Tukey HSD comparisons further indicated that senior firefighters prioritised heat resistance significantly more than junior personnel, reflecting greater accumulated

exposure to high-temperature environments, while long-tenure professionals placed greater emphasis on durability, likely owing to heightened awareness of footwear degradation over extended service. These findings confirm

that experience level meaningfully shapes feature prioritisation, underscoring the need for redesign approaches that address the differentiated requirements of personnel across career stages.

Table 3: Group comparison analysis

Variable	F-statistic	p-value	$\eta^2$
Heat resistance priority	12.34	<0.001	0.089
Comfort importance	8.67	<0.001	0.064
Durability concerns	6.45	0.002	0.048

Post-hoc Analysis (Tukey HSD):

- 1) Senior firefighters prioritize heat resistance significantly more than junior staff ( $p < 0.001$ );
- 2) Experienced personnel (>15 years) emphasize durability more than newer staff ( $p = 0.003$ ).

## Interview Results Analysis

### *Quantitative Summary of Qualitative Responses*

Analysis of the 75 firefighter interviews revealed consistent and pervasive dissatisfaction with current footwear across multiple operational dimensions. Weight and mobility restrictions emerged as the most widely reported concern, cited by nearly all respondents, closely followed by breathability and thermal comfort issues and inadequate heat protection, each reported by a substantial majority. Poor traction on wet surfaces and discomfort during extended operations were also prominently featured, with more than four in five respondents identifying these as significant challenges. Flexibility limitations and durability concerns were raised by approximately three-quarters of the sample, while difficulties with quick donning and doffing, foot fatigue and injury risk, and maintenance challenges, though reported by a somewhat smaller proportion, nonetheless reflect meaningful operational burdens. The convergence of these findings across a geographically and experientially diverse interview sample underscores the systemic nature of current footwear deficiencies, and lends strong qualitative support to the quantitative survey findings reported earlier.

### *Design Requirements Synthesis*

Triangulating findings from both the survey and interview data, an evidence-based priority ranking of critical footwear requirements was established by combining quantitative priority ratings with qualitative reporting frequency. Enhanced heat resistance up to 300°C was confirmed as the foremost requirement, ranking first in the survey and among the highest in interview frequency, reflecting the thermal demands of operational firefighting environments. Improved breathability and comfort, and reduced weight and bulk, secured the second and third combined ranks respectively, with both features recording exceptionally high interview frequency despite comparatively modest survey priority scores, suggesting that these concerns are more acutely articulated through experiential accounts than formal rankings. Better water resistance and enhanced slip resistance occupied the fourth and fifth positions, each supported by strong evidence across both instruments. Improved flexibility, while absent from the formal survey rankings, featured prominently in interview data and was accordingly assigned the sixth combined rank. Better durability and ease of quick donning and doffing consistently occupied the lower end of the priority spectrum across both data sources, though they remained relevant considerations. The convergence of survey and interview evidence across these eight requirements provides a robust, empirically grounded foundation for the subsequent design specification and prototype development phases of this research.

Table 4: Critical Requirements (Evidence-Based Priority Ranking)

Requirement	Survey Priority	Interview Frequency	Combined Rank
1. Enhanced heat resistance (300°C)	1 (33.2%)	3 (89.3%)	1
2. Improved breathability/comfort	5 (10.9%)	2 (92.0%)	2
3. Reduced weight and bulk	3 (12.7%)	1 (94.7%)	3
4. Better water resistance	2 (15.1%)	4 (85.3%)	4
5. Enhanced slip resistance	4 (11.8%)	4 (85.3%)	5
6. Improved flexibility	Not ranked	6 (77.3%)	6
7. Better durability	7 (4.8%)	7 (73.3%)	7
8. Quick donning/doffing	8 (2.8%)	8 (68.0%)	8

**Comparison with Global Standards and Literature**

*Performance Gap Analysis*

Comparative gap analysis between current Indian protective footwear and international standards [5] revealed statistically significant deficiencies across all four parameters. Heat resistance was the most critical, with Indian footwear frequently performing below the international minimum threshold ( $p < 0.001$ ). Average boot weight exceeded the internationally preferred ceiling, representing a moderate but significant gap ( $p = 0.023$ ). Flexibility showed a major shortfall, with current footwear achieving considerably less ankle range of motion than the stipulated minimum ( $p < 0.001$ ). Water resistance performance was inconsistent relative to the

IPX6 equivalent benchmark ( $p = 0.012$ ) [12]. Collectively, these findings provide statistically grounded evidence of systemic performance inadequacy in existing Indian protective footwear, reinforcing the rationale for specification-driven prototype development.

*Comparative Analysis of Existing Protective Footwear Designs & Proposed Footwear*

A comparative analysis benchmarking the proposed designs against existing products covers: (i) current Indian IS 15298 market boots representing standard procurement, and (ii) two proposed prototypes — Design A and Design B. Data for the prototype designs are drawn from component qualification and assembled boot testing conducted at the collaborating BIS-approved laboratory, in accordance with conformity assessment procedures [13].

Table 5: Comparative performance analysis: current Indian market boots and proposed prototypes

Parameter	Current Indian IS 15298 Market Boots	Design A — Prototype 1	Design B — Prototype 2
Heat resistance — sole	300°C/1 min (IS 15298 minimum; often inconsistently achieved)	300°C/1 min ✓ (Nitrile Fire & Ice compound)	300°C/1 min ✓ (Nitrile Fire & Ice compound)
Breathability (MVTR at 38°C)	~128 g/m <sup>2</sup> /24h typical (IS 15298: not specified)	487 g/m <sup>2</sup> /24h (+280% vs Indian market; +21.8% vs 400 g/m <sup>2</sup> /24h threshold)	487 g/m <sup>2</sup> /24h (same Tex membrane)
Weight per pair	2.8–3.5 kg average	2.02 kg ✓ (target ≤2.2 kg)	2.31 kg (0.11 kg above 2.2 kg target; TPU panel trade-off)
Ankle ROM (% unshod)	60–70% typical	~83% ✓ (target ≥80%)	~73% (design trade-off accepted for industrial protection)
Slip resistance (CoF, wet tile)	≥0.28 (IS 15298 minimum; typically 0.28–0.33)	0.44 CoF (+57% above IS minimum)	0.44 CoF (+57% above IS minimum)
Emergency doffing time	No mechanism; >60 s	12.4 s (SD=1.3; n=3) ✓ — Protected Rapid-Release Closure System	23.7 s (triple closure; partial — no equivalent mechanism in current market)

Parameter	Current Indian IS 15298 Market Boots	Design A — Prototype 1	Design B — Prototype 2
Anthropometric fit (Indian foot)	European last standard — documented poor forefoot/arch fit in Indian populations [14]	UK size 8- Kanpur-evolved Indian last: wider forefoot, reduced medial arch height; confirmed by manufacturer design team	Same Indian last as Design A

Both prototypes were designed to deliver substantial performance improvements over current Indian market boots across all critical parameters. Design A was developed to meet weight, ankle flexibility, and emergency doffing targets, with breathability and slip resistance specifications significantly exceeding IS 15298 minimums, and the Protected Rapid-Release Closure System proposed to enable rapid doffing in under 15 seconds. Design B, incorporating an external TPU ankle panel for enhanced structural protection, was designed with acknowledged trade-offs in weight and ankle ROM. Both prototypes share identical thermal barrier specifications, breathability, slip resistance, and an Indian-last anthropometric construction.

## DESIGN THINKING APPLICATION AND SOLUTION FRAMEWORK

Design thinking provides a structured yet iterative methodology for translating empirical user insights into functionally differentiated design solutions, integrating deep stakeholder engagement with evidence-based ideation and prototype validation [15, 16].

### Empathize Phase: Comprehensive User Understanding

A mixed methods approach integrated survey data (n=385; Cronbach's  $\alpha=0.89$ ) and semi-structured interviews (n=75) to elucidate user needs and challenges with empirical rigor.

#### Primary User Personas (Evidence-Based)

Cluster analysis identified three distinct user personas — Urban Firefighter, Industrial Emergency Responder, and Rural/Wildland Firefighter — each exhibiting differentiated operational contexts and footwear priorities. These findings affirm that a single uniform footwear specification is inadequate to address the heterogeneous needs of India's disaster management workforce.

K-means clustering (k=3, silhouette score=0.72) delineated three personas.

**Persona 1 – Urban Firefighter (60%, n=231):** High-rise operations; needs lightweight, flexible, quick-don designs. Challenges: confined-space mobility, prolonged discomfort. Priorities: weight reduction (mean=4.82, SD=0.41), breathability.

**Persona 2 – Industrial Emergency Responder (25%, n=96):** Chemical/thermal hazards; needs protective, durable gear. Challenges: heat shielding, permeation risks. Priorities: heat resistance (mean=4.71, SD=0.52), chemical protection.

**Persona 3 – Rural/Wildland Firefighter (15%, n=58):** Extended terrain deployments; needs terrain-adaptable, resilient comfort. Challenges: traction, endurance. Priorities: slip resistance (mean=4.65, SD=0.48), durability.

### Prototype Phase: Design Specification Development

#### Core Design & Material Selected

Material and component configurations were evaluated sequentially against four criteria, with progressive elimination employed until an optimal nine-component stack was identified. The primary criterion was thermal protection performance, requiring resistance to contact heat up to 300°C for three minutes at the outsole, an effective radiant heat barrier [17], and flame resistance with no continued burning. The second criterion concerned total assembled thickness, stipulating that the boot must fit on an Indian-specific last without excess bulk. Weight per pair constituted the third criterion at 2.5 kg or less per pair, with Carbon-Kevlar composites preferred over steel toecaps on account of a 61% weight saving. The fourth criterion addressed production feasibility, requiring fabricability within Indian manufacturing facilities using available skilled labour.

The final material architecture comprises a nine-component stack. The outer shell employs 2.2mm flame-retardant, water-resistant, full-grain chrome-tanned leather in rough-out orientation, tested in accordance with IS 2387 [18]. An aluminised para-aramid felt thermal barrier intercepts conductive and radiant heat between the outer shell and the membrane assembly, while localised Kevlar woven fabric patches bonded at high-stress upper zones provide cut resistance, puncture resistance, and thermal stability. The waterproofing and moisture management assembly spans three sub-components: a PBI/meta/para-aramid flame-resistant substrate; an expanded PTFE microporous membrane; and a hydrophilic polyurethane monolithic coating with thermally bonded seam sealing. The multi-density memory foam insole delivers fatigue reduction across operational shifts of twelve hours or more. The Nitrile rubber Fire and Ice outsole offers traction across  $-40^{\circ}\text{C}$  to  $+300^{\circ}\text{C}$ , SRC-rated slip resistance, and chemical and oil resistance. The Carbon-Kevlar composite midsole plate and toecap, rated at 400N and 200J/15kN respectively, provide puncture and impact protection at 61% less weight than steel equivalents.

### Design A & Design B Prototypes

K-means cluster analysis identified three statistically distinct user personas. Persona 1, the Urban Structural Firefighter, representing the largest segment, prioritised rapid movement, quick donning and doffing, and minimal weight in high-rise operational contexts, directly informing Design A — a low-mid ankle boot with the Protected Rapid-Release Closure System and a target weight of 2.2 kg. Persona 2, the Wildland and Forest Firefighter, prioritised lower leg protection, ankle support on uneven terrain, and extended field durability, informing Design B — a tall shaft boot incorporating an external TPU ankle panel and triple-element closure system. Persona 3, the Industrial Emergency Responder, centred on chemical fire response, contaminated surface traction, and chemical permeation resistance; however, this persona was designated a scope exclusion as the requisite Class II all-rubber construction falls outside the Class I leather upper framework of this research. Accordingly, the present research considers Design A and Design B as the two prototype configurations taken forward for specification development, fabrication, and performance validation, with Design C excluded from the scope of this study.



Figure 3. Design A (Persona 1) & Design B (Persona 2)

### Design Features

**Design A** is configured as a low-mid ankle boot with a shaft height of approximately 160mm, optimised for urban agility and stair navigation. Against a target weight of 2.3 kg per pair, the prototype achieved 1.90 kg per pair. The closure system employs a waterproof

zipper concealed beneath a wide Velcro protective flap, forming the basis of the key design innovation — the Protected Rapid-Release Closure System — which enables emergency doffing in under 15 seconds through single-hand operation. Ankle range of motion is maximised at approximately 83% of unshod ROM [2], facilitating multi-storey

movement. Design A achieved full IS 15298 (Part 2):2024 compliance [4].

**Design B** is configured as a tall shaft boot with a shaft height of approximately 265mm, designed to provide lower leg flame protection and mechanical debris resistance for wildland and terrain-based operational contexts. Against a target weight of 2.6 kg per pair, the prototype achieved 2.2 kg per pair. Ankle protection is enhanced through an externally moulded TPU panel at the lateral and medial malleolus zones. Ankle range of motion is approximately 73% of unshod ROM, representing a deliberate protection-mobility trade-off. Both designs share an identical nine-component material architecture, Indian-specific last geometry [14], Carbon-Kevlar composite toecap rated at 200J and 15kN, Nitrile rubber Fire and Ice outsole, ePTFE layer bicomponent membrane bootie, aluminised para-aramid and Kevlar patch reinforcement system, multi-density memory foam insole, integrated ankle protection, and cemented construction.

### Test Phase: Validation Framework Development

#### *Laboratory Performance Analysis — BIS-Approved Testing*

Both prototype configurations were subjected to performance evaluation at a BIS-approved laboratory [13], with all specimens conditioned in accordance with BIS standard procedures prior to testing [4]. Design A was further validated against all ten mandatory IS 15298 (Part 2):2024 test parameters, achieving full compliance across every criterion. Outsole abrasion resistance was recorded at 139 mm<sup>3</sup> against a maximum permissible threshold of 150 mm<sup>3</sup>, reflecting a 7.3% safety margin. Nail perforation resistance exceeded the minimum requirement of 1,100N by 11.9%, achieving 1,231N. Upper-to-sole bonding strength was recorded at 6.0 N/mm, surpassing the 4.0 N/mm minimum by 50%. Toecap impact resistance achieved 17.52mm internal clearance against the 14.00mm minimum (a margin of 25.1%), while toecap compression resistance recorded 17.46mm clearance, exceeding the threshold by 24.7%. Hot contact resistance at the sole passed fully at 300°C for three minutes with no melt or damage. Flame

resistance was assessed across four separate components — upper leather, tongue, stitching thread, and quarter lining — with all four self-extinguishing upon removal of the flame source, confirming the integrity of the flame-retardant material system throughout the upper assembly.

Breathability, unspecified under IS 15298, was measured at 487 g/m<sup>2</sup>/24h for both prototypes [19], representing a 280% improvement over typical Indian market performance of approximately 128 g/m<sup>2</sup>/24h and exceeding the self-imposed threshold of 400 g/m<sup>2</sup>/24h by 21.8%. Design A achieved 2.02 kg per pair within the 2.2 kg target, while Design B recorded 2.31 kg as a documented trade-off attributable to the external TPU ankle panel. Slip resistance was identical across both prototypes at 0.44 CoF on wet tile [12], exceeding the IS 15298 minimum of 0.28 CoF by 57%. Emergency doffing time presented the most marked differentiation; Design A achieved 12.4 seconds via the Protected Rapid-Release Closure System, well within the 15-second target, while Design B recorded 23.7 seconds through its triple-element closure. Both prototypes were constructed on an Indian-specific anthropometric last derived from Kanpur-based practitioner measurements, incorporating a wider forefoot and reduced medial arch height relative to European standard lasts [14]. Collectively, the laboratory results confirm that both prototypes meet or exceed all applicable IS 15298 [4] mandatory thresholds, with conformity assessment procedures followed throughout [13].

Both prototype configurations — Design A and Design B — were subjected to performance evaluation at a BIS-approved laboratory, with all specimens conditioned in accordance with BIS standard procedures prior to testing. Design A was further validated against all ten mandatory IS 15298 (Part 2):2024 test parameters, achieving full compliance across every criterion. Outsole abrasion resistance was recorded at 139 mm<sup>3</sup> against a maximum permissible threshold of 150 mm<sup>3</sup>, reflecting a 7.3% safety margin. Nail perforation resistance exceeded the minimum requirement of 1,100N by 11.9%, achieving 1,231N. Upper-to-sole bonding strength was

recorded at 6.0 N/mm, surpassing the 4.0 N/mm minimum by 50%. Toecap impact resistance achieved 17.52mm internal clearance against the 14.00mm minimum, a margin of 25.1%, while toecap compression resistance recorded 17.46mm clearance against the same threshold, exceeding it by 24.7%. Hot contact resistance at the sole passed fully at 300°C for three minutes with no melt or damage. Flame resistance was assessed across four separate components — upper leather, tongue, stitching thread, and quarter lining — with all four self-extinguishing upon removal of the flame source and achieving full pass status, confirming the integrity of the flame-retardant material system throughout the upper assembly.

## CONCLUSIONS

This study set out to address a critical and underexplored gap in Indian disaster management preparedness — the systematic inadequacy of protective footwear available to operational firefighting personnel. Through a rigorously designed mixed-methods framework encompassing a statistically validated survey of 385 professionals across six states, 75 in-depth interviews, comparative gap analysis against international standards, and evidence-driven prototype development, the research has generated a comprehensive, empirically grounded contribution to the field of protective footwear design in the Indian context.

The empirical findings unambiguously established that existing IS 15298-compliant market footwear falls short across multiple critical performance dimensions, with thermal protection, traction, weight, breathability, and anthropometric fit emerging as the most pressing deficiencies. The near-unanimous consensus among respondents regarding the necessity of redesign — supported by robust statistical evidence — underscores the urgency of the problem and validates the central premise of this research. Cluster analysis further revealed that India's disaster management workforce is not a homogeneous user group, and that persona-differentiated design approaches are essential to adequately address the heterogeneous operational realities encountered across urban, wildland, and industrial deployment contexts.

The design thinking methodology adopted in this study enabled a structured translation of empirical user insights into two functionally differentiated prototype configurations. Design A, optimised for urban structural firefighting, achieved full IS 15298 (Part 2):2024 compliance across all ten mandatory test parameters, while simultaneously surpassing self-imposed performance targets for weight, breathability, slip resistance, ankle mobility, and emergency doffing time. The Protected Rapid-Release Closure System, for which a provisional patent application is in preparation, represents a novel design innovation with direct implications for operational safety. Design B, configured for wildland and terrain-intensive deployment, introduced deliberate and documented design trade-offs in favour of enhanced lower leg and ankle structural protection, while maintaining identical material architecture, thermal performance, and anthropometric fit as Design A.

Collectively, both prototypes demonstrate that it is feasible to develop IS 15298-compliant protective footwear that meaningfully surpasses current Indian market performance, incorporates Indian-specific anthropometric geometry, and addresses the operational priorities of end users — within the constraints of Indian manufacturing capabilities and supply chains. The research thereby contributes an evidence-based design specification, a validated nine-component material architecture, and a replicable methodology for user-centred protective equipment development applicable to the broader domain of occupational safety in India. Future research should address longitudinal field validation of both prototypes under operational conditions, wearability and fatigue studies over extended shifts, and the development of a Class II equivalent design to address the industrial emergency responder persona currently excluded from this study's scope. Standardisation of breathability [19] and weight thresholds within IS 15298 [4] revisions is also recommended, given the empirical evidence presented here for their operational significance, and in alignment with national fire and emergency service guidelines [20].

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